FINAL REPORT

ON

DISSOLVED OXYGEN LEVELS

IN SELECT MAINE

ESTUARIES AND EMBAYMENTS

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INTRODUCTION

Nutrient enrichment and eutrophication of marine and estuarine waters is a growing environmental concern (e.g., Nixon, 1990). One principle concern is that elevated metabolism (productivity and respiration) will ensue and eutrophication will cause dissolved oxygen (DO) concentrations to decrease far below normal seasonal levels. Low DO (hypoxia) or the absence of DO (anoxia) endangers the vitality of marine and estuarine ecosystems and organisms, including commercial species. Anoxia and hypoxia have been experienced in Chesapeake Bay (Officer et al., 1983), New York Bight (Falkowski et al., 1980), and Long Island Sound (Parker and O'Reilly, 1991) as well as at the heads of some smaller northeastern US coastal systems where nutrient loads are high and there is restricted water exchange. As one of a suite of possible ecological endpoints for eutrophication, DO is a prime indicator for coastal marine waters.

A number of comparative efforts for freshwater and marine ecosystems have demonstrated strong relationships between nutrient loads and the concentration of nutrients, chlorophyll, and the level of primary production (e.g., Vollenweider, 1976; Nixon et al., 1986; Kelly and Levin, 1986; Oviatt et al., 1986; Nixon, 1992; Monbet, 1992). A given level of nutrient load may not lead to the same ecological conditions, nor will it induce a similar oxygen depression, in every coastal system. Actual nutrient concentrations and the expression of metabolism as lowered DO can be influenced by many biological, chemical, geomorphological, and physical factors like water residence time (e.g. Valiela and Costa, 1988; Kelly, 1995) and stratification (e.g., Turner et al., 1987). Even so, there have been successful comparative efforts to relate DO and nutrients; for example, Jones and Lee (1986) showed a significant relationship between rates of hypolimnetic (bottom-water during seasonal lake stratification) DO decline and residence-time normalized nutrient loads.

Maine has a extraordinary length of coastline and many small coastal water bodies. It is not yet known whether there are significant or pervasive DO problems, so data are being collected (a collaborative effort by Wells NEER and MDEP) to assess the issue. The potential ecosystems are numerous and comprehensive study of individual systems needs to be supplemented with broad studies of a range of systems. In 1995, an approach was taken to study a selection of systems, including those which are thought vulnerable to depressed DO and those which are not expected to be susceptible to the problem. Using survey data on DO, associated environmental variables, and physical/morphological characteristics of the ecosystems, the intent is to gain insight into factors influencing DO in Maine coastal waters.

This task reports on extensive exploratory analyses of the data collected and assembled for a set of coastal systems sampled in 1995. The goal was to identify and describe relationships among DO and other factors. The overall goal of the data collection and analyses efforts is to define a relationship(s) that could serve as an index to broadly classify susceptible areas and aid planning for source control of nutrients to all coastal water bodies in Maine.

METHODS

For this study, data were provided for nineteen ecosystems along the Maine coast from New Hampshire to Canada (Figure 1). These systems represent a wide variety of geomorphic, hydrologic, and loading conditions; information in Table 1 was provided to Battelle by the Maine Department of Environmental Protection.

The field studies took place from July to September 1995. Most systems were sampled during each of the three months. The data set consisted of station location, sampling date and time, temperature (°C), salinity (ppt), conductivity (mS/cm), dissolved oxygen concentration (mg/l, [DO]) and %saturation (%SAT), and depth (ft). After preliminary screening and removal of a few outliers, we used the data from sampling (n=3611 total events) and for the system attributes (Table 1) in the analyses for this report

The data provided a number of potential explanatory variables for DO in the selected Maine estuaries and embayments.

Sampling	location, depth, time, date, tidal stage
Environmental	temperature, salinity
Morphometrics	area, perimeter, volume, length, width, volume, max. depth, x-c area (mouth), sill location and size
Circulation	mean tidal range, max. tidal range, mean tidal volume, mean tidal current, peak tidal current, flushing times, freshwater vol./saltwater vol.
Freshwater Input	watershed area, freshwater discharge (June through Sept.), nutrient loading, area of watershed/area of surface water

Some initial efforts focused on determining appropriate dissolved oxygen metrics. An overview of the DO and %saturation data was provided by univariate statistics for each system. In addition, numerous box and whisker plots were produced of DO and %SAT by system over a variety of spatial and temporal scales: all data, all low tide data, all high tide data, all bottom depth data, and similar groupings on monthly time scales. A number of vertical contour plots were produced to better illustrate some of the system-wide and tidal variations observed in the data.

Battelle has a full compliment of computer software to allow contouring of spatial and temporal trends (Surfer), spreadsheet/graphics (QuattroPro, Excel), and full range statistical analyses/graphics (SAS). These software programs were used to conduct the variety of analyses, some briefly highlighted next.

All statistical testing (regression, comparison tests of difference, principal components analysis) was conducted in SAS. Tests were made by non-parametric (Kruskal-Wallis test) and parametric (ANOVA) methods. For ANOVA and its follow-up planned comparison tests (Tukey's Studentized Range), we attempted to stabilize the variance by a variety of transformations. None appeared particularly better than the raw data, so we used untransformed DO concentrations. In this report, results are described as significant differences if non-parametric tests showed significance at the 95% level. With significance in the non-parametric test, further parametric testing was conducted, including the planned comparison test to look for differences across groups within the data set. All planned comparison tests were conducted at the 95% significance level. Results of parametric tests must be viewed with caution, but certainly are useful in an exploratory exercise.

RESULTS

Overview of DO Patterns

Range and frequencies
For the entire data set, the frequency distribution of all observations (n=3611) is shown in Figures 2 and 3, for concentration and % saturation, respectively. The majority of the observations had a DO concentration of ~7 to 9 mgL^{-1} and represented conditions that were ~90 to 105% of saturated values for each *in situ* condition. Far fewer than 1% of the observations were <5 mgL^{-1}, a level below which some subtle biological effects of lowered DO may begin to be expressed (personal communication: D.C. Miller, U.S. EPA, Narragansett, RI).

DO variability over time and space of sampling
Examining the entire data set, DO varied as a function of month of sampling, stage of tide/time of day, and depth of sampling. For example, testing showed that DO concentrations, as well as % saturation values, were different for surveys in July, August, and September (Kruskal-Wallis Test, Prob > Chisq = 0.0001, df=2). By planned comparison tests, mean DO concentrations (and % saturation) were different among each month. The mean DO decreased significantly from a mean value of 8.97 mgL^{-1} in July to 8.42 mgL^{-1} in August and 7.78 mgL^{-1} in September. The mean % saturation also decreased over time — from 109% in July to 103% in August and then to 93% in September. Further testing showed that the time course of DO concentrations differed among systems and in spite of the overall trend, not all systems showed a significant and progressive decrease from July to September. Additionally, similar tests that compared the bottom-water DO concentration over months, with data restricted to the low tide sampling, confirmed a progressive decrease and month-to-month differences. Mean low tide bottom DO concentrations were 9.01, 7.9, and 7.25 mgL^{-1} , respectively in July, August, and September. Figure 4 gives an example of the general decrease in DO throughout New Meadows River over the period of surveys in 1995. The figure also suggests there is spatial complexity to within-system DO variability. Features like depth and position along the axis of the system sometimes influence the measured DO concentrations, as discussed later.

With respect to tidal stage, tests were conducted using only those systems which had a repeated sampling early in the day (low tide) and later in the day (near high tide). Separate tests were conducted for July (n= five systems), August (n= 10 systems), and September (n=7 systems). In each month, the DO concentrations differed significantly between samplings. Interestingly, in July the mean DO at high tide (8.42 mgL^{-1}) was lower than at low tide (9.52 mgL^{-1}). In contrast, in both August and September, DO was significantly lower at low tide. Mean concentrations in August were 8.28 mgL^{-1} and 8.54 mgL^{-1} at low and high tide, respectively. Mean concentrations in September were 7.45 mgL^{-1} and 8.11 mgL^{-1} at low and high tide, respectively. The difference between tidal trends in Jul and the other months may in part relate to a sampling that was not as close to low tide as the other months. Figure 5 provides two different examples of changes in DO as a function of time of sampling. Little River is a shallow system where the tidal exchange volume represents most of the water in the system at high tide. The DO concentration at high tide was uniformly high, as was salinity (Figure 5b). At low tide, DO concentrations were lower throughout the system, especially near the bottom. The difference between high and low tide salinity was also striking in this system. Somes Sound is one of the deepest of the 19 systems sampled and has a slower tidal flushing than Little River. Salinity changes from between low and high tide were relatively slight, but a generally lower DO was still evident at low tide in this system also. Like Figure 4, Figure 5 shows that there is considerable spatial complexity to the distribution of DO and there are considerable (and significant) changes at tidal timescales, as well as at monthly intervals. As with changes over months, the nature of DO concentration changes over tidal cycles vary with the system.

As is evident in Figures 4 and 5, there was structure in the vertical and horizontal distribution of DO. In most cases, we noted (but did not test) that lower DO was found towards, if not at, the head of the embayment more regularly than near the mouth.. A test for DO differences as a function of depth confirmed overall depth patterns. DO at the surfacemost, bottommost, and midwater sampling depths were compared using all the systems and months of sampling. The test was restricted to low tide sampling. Results confirmed differences with depth (Kruskal-Wallis test, Prob >Chisq =0.0001, df=2) and noted lowest values near the bottom on average. Planned comparisons (95% level) showed that mean bottom DO concentrations (7.96 mgL^{-1}) were significantly lower than the midwater values (8.40 mgL^{-1}). Surface DO concentrations (8.27 mgL^{-1}) were also slightly lower than midwater, but higher than bottom waters. For % saturation, bottom water averaged 96%, middle 101%, and surface 102%. Planned comparison tests indicated that the bottom % saturation was significantly lower than either the surface or midwater values. As with most other tests, additional results confirmed an interaction of depth and system, meaning that in spite of the overall trend of DO minima near the bottom, there were systems which had dissimilar trends.

DO concentrations also varied, in part, as a function of environmental conditions. For example, the entire data set was used to conduct a multiple linear regression analysis using a stepwise procedure to add variables to the model (SAS, 1988). The dependent variable was DO concentration (mgL^{-1}) and the following variables were included as possible dependent variables: day of year (DOY), time of day (TOD), time of sampling relative to tide (TOT), *in situ* temperature (T), *in situ* salinity (S), and depth of sampling (Z). A resulting significant regression model that explained 26% of the variability in the data ($r^2 = 0.259$) was:

$$DO = 10.29 - 0.028\ DOY - 0.023\ T^2 + 0.66\ T.$$

The first dependent variable added, DOY, accounted for almost 20% of the variance. Further addition of TOD, TOT, and S variables (or squared values thereof) slightly improved the model ($r^2 = 0.296$), but had lesser influence and did not fundamentally alter the result above. The results suggest a prime explanatory variable was the month of sampling and confirm the statistical result above of a DO decrease over time in the systems of study. The coefficient for DOY suggests an average decrease of 0.028 $mgL^{-1}\ d^{-1}$, which is reasonably consistent with some observations in other temperate marine ecosystems. A secondary influence was the local temperature as a non-linear term negatively influencing DO. This term, in principle, may be consistent with general observations of an exponential increase in respiratory metabolism with increasing temperature. Interestingly, each of these terms explained more variability than TOD/TOT variables relating to sampling times within the day. The model above suggests an influence of the local and perhaps seasonal environment, but nonetheless explains a small portion of the DO variability. In principle, this leaves the majority of the variability in the DO data set to be explained by other factors, such as different characteristics of the 19 systems included in the overall data set.

DO patterns across systems

For the cross-system comparisons considered next, box and whisker plots are a tool for an efficient visual summary of statistical information on the sampled distribution of DO. The upper and lower ends of the box represent the upper (75th) and lower (25th) quartiles. The length of the box is equal to one interquartile range and indicates the spread of 50 percent of the observations. The line within the box represents the median (50th quartile). The distribution of the data, symmetrical or skewed, can be seen from the location of the median relative to the upper and lower ends of the box. The vertical lines (whiskers) extend to the most extreme values that are within 1.5 interquartile range above and below the box. In a normal distribution, the range of the box and whisker plot includes ~99% of the observations. Values outside the range of the plots ("outliers" or "extreme" values) are marked with a plus.

An initial effort was made to develop simple DO metrics for characterizing each system with respect to DO and to be used in a preliminary assessment of possible relationships of DO with morphometry and other attributes that varied across the systems. Spatial and temporal sampling within each system was not sufficient to resolve the areas or volumes associated with DO concentration classes. In consultation with M. Dionne and J. Sowles, and furthermore considering the results of analyses on the whole data set above, we focused on the following as principal DO metrics: 1) the mean DO for each system, 2) all low tide bottom samples within a system in September, 3) extreme DO values as characterized by the mean of the lowest 5% (by ranking) of the measured DO values in each system, independent of location or time of collection, and 4) the absolute minimum value in each system. These metrics, as DO concentrations and % saturation, are summarized in Table 2 and their geographic distributions are next briefly described.

There was a wide range of [DO] and %SAT between systems. The minimum [DO] ranged from 4.49 mgL^{-1} (Spruce Creek) to 7.93 mgL^{-1} (Whiting Bay). The lowest [DO] were observed in the Spruce Creek and Little River systems (<6 mgL^{-1}). The lowest %SAT were also observed in these systems (<70%) and ranged from 54.4% (Spruce Creek) to 94.6% (Taunton Bay). The mean [DO] ranged from 7.11 mgL^{-1} (Little River) to 9.65 mgL^{-1} (Linekin Bay). All systems, except Spruce Creek and Little River (7.66 and 7.11 mgL^{-1}, respectively), had mean [DO] >8.0 mgL^{-1} and a majority of these systems were supersaturated with a mean %SAT >100% (Table 2 and Figure 6a & 6b).

Generally, there were relatively large ranges in both [DO] (~5 mgL^{-1}, Figure 6a) and %SAT (~60%, Figure 6b) within each system. The general trend in Figures 6a and 6b was that relatively lower means in [DO] and %SAT were observed in the southern systems. Many of the highest means were observed for the downeast systems, but a high mean DO was also observed at Fore River. The values observed in middle of the coast, including the Casco Bay systems, displayed the widest ranges for both parameters.

There were strong similarities in the distribution, trends, and relative values of [DO] and %SAT, as indicated in Table 2 and Figures 6a and 6b. In order to present the considerable volume of data clearly, the primary emphasis of this report is on [DO], but some analyses are also conducted on % saturation for all data within a system.

The general geographic patterns described for the mean [DO] and %SAT metrics across systems tended to hold true for the lowest 5% [DO] (Figure 7a) and September low tide bottom water (Figure 7b) metrics. Additionally, the months in which the lowest 5% [DO] measurements were taken vary between the three groups of systems. In the southern systems, the lowest 5% [DO] occur over all three months of sampling, while at the Casco Bay systems most of the low [DO] measurements occurred in August and in the downeast systems most occurred in September. Within systems, the lowest 5% [DO] measurements occurred over a range of stations and depths.

Based on the statistical testing we expected that the lowest [DO] would occur in September at low tide at depth. This was true on average, but individually these data were not necessarily the lowest 5%. This was illustrated in a comparison of the metric means (Figure 8). Quite clearly, the coastwide trends were similar for each of the DO metric means across systems. The most noticeable deviation occurred for Quahog Bay where the mean for the lowest 5% [DO] metric was much lower (~2 mgL^{-1}) than the other metric means. In Quahog Bay, the lowest 5% [DO] were measured in August and the water column was stratified (at station 2).

Statistical tests for differences across systems

For four DO metrics, we tested for differences among systems. Non-parametric and ANOVA tests for each metric (all DO as concentration or % saturation, the lowest 5%, and the low tide bottom water in September) resulted in the conclusion that significant differences (e.g., Kruskal-Wallis test, Prob>Chisq=0.0001, df=18) existed across the 19 systems. Figure 9 displays the results of subsequent planned comparison tests. Since planned comparisons test each system vs. all the others, a large number of comparisons are conducted. Often in such tests, when there are relatively small differences and a continuum across many systems, results will indicate a series of overlapping groups of similar (with respect to the metric) systems. Such a result is shown in Figure 9a. Two systems, the one with the lowest DO (Little River) and the highest mean DO (Linekin Bay), were distinctly different from the rest. There was a group of systems with higher DO, including Taunton Bay, Back Cove, Whiting Bay, Boothbay Harbor, and Fore River, that were distinctly different from the rest. At the lower end, Spruce Creek was lower in DO than most of the systems. In the middle of the DO range, were 11 or more systems that were similar to each other and all had [DO] means between 8 and 9 mgL^{-1}.

Results for the mean % saturation suggested that both Little River and Spruce Creek were significantly different from each other and from the remainder of the systems. These two systems were distinctly heterotrophic, as they had mean % saturation values well below 100%.

There were apparent differences between the most supersaturated, and thus autotrophic systems (e.g. Fore River, 114%) and those with more balanced trophic status during the sampling period, i.e. near 100% saturation (e.g., Biddeford Pool, Somes Sound, Union River Bay). But overall, a gradual continuum of % saturation is suggested by the statistical comparisons.

Using the lowest 5% of the concentrations, Little River again was significantly lower than others (5.41 mgL^{-1}). Lower extreme DO conditions also occurred in Quahog Bay and Spruce Creek compared to most other systems. Most other systems were somewhat similar with respect to their measured extreme (but rare) events, although two subsets were suggested. One had rare conditions below 7 mgL^{-1} and included a group of about 5-7 systems. The other had its lowest measured DO conditions ranging from 7.20 to >8 mgL^{-1} (Whiting Bay).

The final metric examined was the low tide bottom water mean for each system as measured in September, the month with lowest average DO conditions. As somewhat characteristic, Little River was the lowest (<5.91 mgL^{-1}) and Whiting Bay (8.37 mgL^{-1}) was the highest, but neither was fully distinct from other systems by the comparisons. Although September had the lowest DO concentrations on average, the spatial variability at bottom waters of stations within each system was apparently large and probably masked differences in localized conditions that might be more apparent with analyses of spatial heterogeneity that might be aided by more intense within system sampling.

Overall, the comparisons of DO suggested differences among systems. But due to spatial and temporal variability within the systems and relatively small inter-system differences on the whole , only several systems at the extremes of the DO range were very distinct. Chief among these were Little River (low) and among others, Fore River (high for mean Do and % saturation), both highlighted here to be referenced in later discussion.

Overview of System Attributes

Environmental

Boxplots were also developed for temperature (T) and salinity (S) data collected at the time of DO sampling (Figure 10a,b). As for DO, there was considerable variability in T and a substantial range within each system. In contrast, S data show quite a narrow range for most systems and high salinities generally averaging around 31-33 ppt. For the most part these are not estuarine systems with high volumes of freshwater input. From Figures 10 and 11, one can see that three systems in particular stood out for lower salinity on average and a much greater variability in the range of salinity sampled. These systems were Little River, Pleasant River, and Union River Bay.

Morphometrics, circulation, flushing attributes

Using data provided to us (Table 1), we produced a series of bar graphs to compare system attributes. Several parameters are shown in Figures 12 and 13. At first glance the systems appear to be grouped roughly by many morphometrics according to distance up the coast. The southern systems (south of Portland), middle (Casco Bay) systems, and downeast systems each have groups of somewhat similar systems in some regards.

A correlation analysis of the morphometrics determined that there were high degrees of correlation between many of the physical metrics ($r>0.8$, where $p>>0.05$ given that $n=19$). [Note: For $n=19$ ($df=17$), r values ≥ 0.46 suggest a significant relationship at the 95% level]. The co-linearity among parameters is not surprising as many were used in calculating others (e.g., watershed area and all the FW runoff volumes) or are fairly analogous to other metrics (eg. length and perimeter, or areas and volumes). The correlation results were used to reduce the list of morphometrics to eight (see Table 3), but most of these were still rather highly correlated. Further, a principal components analysis (PCA) suggested that a majority of the variability among the either the entire set or the reduced set of eight parameters could be accounted for by the first principal component. Examination of the loading coefficients for each parameter of the first principal component strongly suggested the single general factor explaining most of the difference in system attributes was characterizable as the overall size of the system. Embayment areas and volumes, tidal volumes, runoff volumes, watershed area were some of the aspects of size indicated by the PCA and shown as highly correlated in Table 3. Additional principal components, explaining a minor portion of the variability across systems, were apparently related to factors like the shape of the system or dynamic features like the relative amount of freshwater input and/or mean tidal range.

DISCUSSION: RELATION OF DO TO SYSTEM ATTRIBUTES

Initial Correlation Analysis

Correlations among the different DO metrics were all significant at the 95% level (Table 3). A comparison of the oxygen metrics showed a very high correlation between lowest value and lowest 5% mean value for both DO and %SAT. Also, as expected, DO and %SAT metrics were highly correlated with each other.

A linear correlation analysis also was performed for the eight system morphometrics versus the eight dissolved oxygen metrics. There were few significant correlations when DO metrics were compared to system attributes (Table 3b). The significant r values involved attributes of perimeter, mean tidal range, and width and are difficult to interpret. Actually, only 4 out of 64 (6%) of the possible correlation coefficients were significant; thus, these may be statistical artifacts more than meaningful relations.

Review of Intended Study Design

Chosen systems
Figure 14 is an attempt to display the intended two-factor contrasts offered by the study design, as indicated to us by the project team. Systems were sampled that represented a gradient of flushing times as estimated by tidal flushing times. Additionally, systems were sampled to represent a range of relative loading rates as indicated by a qualitative ranking, where Fore River was an example receiving high loading. The resultant design was intended to be roughly a 3 by 3 matrix (low-medium-high for each factor), but of the extreme factor contrasts only the low loading-slow flushing time condition represented by Linekin Bay had an example system. The conceptual model here is clear — that DO might be a function of flushing, where slowly flushing systems might have a tendency towards lowered DO. Additionally, high loading in principle can increase metabolism and the potential for lowered DO. Thus, the worst conditions for low DO might result from higher loading and long flushing times.

Relation to DO
Quite clearly, the conceptual model, using Figure 14 as the guide for system ranking with respect to the two factors, is not supported by the DO data. For one, Little River had significantly lower DO than most, if not all systems, yet it is apparently flushed fast and only has medium loading. At the other extreme, the condition with highest relative loading, Fore River, stood out as among those with the highest, not the lowest DO. Note that given the results in Figure 9, the task of linking DO and system attributes amounts, as a simplistic exercise, to explaining the significantly low DO conditions in Little River and the higher DO conditions in Fore River.

For the latter, Fore River, it seems reasonable to suggest that loading to that system stimulates production and results in a net autotrophic system, which is one possible consequence of nutrient stimulation. It would seem that flushing of this system, although ranked as medium, is fast enough and mixing rigorous enough to assimilate the loading. In general, although conceptualized as three classes of flushing, *all* the flushing times are within several days and relative to other estuaries, these are all rather rapidly flushed systems. On the other hand, a mean flushing time, as calculated, can overestimate true flushing because sloshing of some of the water in and out of the estuary/embayment occurs before complete release to the coastal marine water and flushing is not completely efficient. Moreover, an average flushing for a whole system can poorly represent conditions within some portions of a physically heterogenous system. Nonetheless, as a guide, the flushing factor may be roughly correct in terms of systems ranked in this study.

Other Aspects of the Array of Sampled Systems

In searching for another conceptual model, we focused on being able to explain the low DO in a system like Little River. When one chooses an array of systems with an intended design, it is not like a controlled experiment when only the factors of interest are manipulated. That, along with a true loading ranking that is different from that given in the figure, may be partially responsible for lack of support for the conceptual model above. In actuality, there are additional factors that are embedded in the design. For example, keying on size as a discriminant across the systems (indicated by PCA), we examined size as typified by the high water area (Figure 15). There is a gradient of size, and a relationship to flushing, with most small systems being among those flushed quickly. Another aspect of size, but one also recognizing shape, is the mean depth at high tide (calculated from high water volume/high water area); mean depth at high tide is displayed as a function of flushing for all 19 systems in Figure 16. Obviously, flushing and depth are related. Smallness itself does not lead to an easy explanation of low DO in Little River and or Spruce Creek, another fairly low DO condition. Note, however, that the impact of benthic oxygen demand on DO in the water column can be more easily magnified in a shallow system, especially if there is some vertical stratification.

We recognized that Little River had a lower salinity than many systems and wanted to examine this feature. Indeed, if one calculates the relative freshwater input (annual watershed runoff/high water volume), it is noticeable that Little River has a high ratio (Figure 17). In one sense, this metric represents a volume-based loading analogy. For example, concentrations in runoff being equal (and higher than seawater concentrations brought in with the tide), runoff from non-point sources will be higher with systems having a high relative runoff for their volume. All systems had a much greater annual tidal exchange volume than a freshwater input. But the relative importance of freshwater input was high in Little River (about 10% of tidal), whereas it was 1% or less in most systems (Figure 18). Moreover, in relation to size (the first principal component and major "factor" of the design, Little River also stands out (Figure 19).

In principle, a relatively higher freshwater input, as calculated, may almost be an indicator of loading (Fore River and its high point source loads perhaps excepted). Alternatively, freshwater input may induce stratification of bottom water (cf. Figure 5), especially between tides when much of the volume of this small system ebbs from the system. Little River's smallness may also allow higher bottom water temperatures and its marshy nature (M. Dionne, personal communication) may be important to creating its lower DO. But, for data exploration, we included the relative runoff metric, as well as depth and the ratio of runoff to tidal exchange, in a list of dependent variables used in multiple regression analyses, as presented next.

Multiple Regression Analyses

In general, we were able to develop significant regressions between DO metrics and combinations of dependent variables of environmental conditions (T,S) attributes from the list in Table 2 and also those composite variables or ratios described above.

Testing was done in stages. First, we examined DO metrics (Table 2) in relation to environmental variables, T, S, and sampling depth. From this, as examples, the following significant models were obtained:

$$\text{DO (mgL}^{-1}\text{, lowest 5\% metric)} = 10.46 - 0.19\,(T) - 0.022\,Z \quad (r^2 = 0.51;\ \text{Prob}>F=0.003)$$

$$\text{DO (mgL}^{-1}\text{, low tide September bottom)} = 2.92 + 0.144(S) \quad (r^2 = 0.26;\ \text{Prob}>F=0.045).$$

These alone explain a substantial degree of variability in the DO metrics across the systems and illustrate an influence of differing in situ environmental conditions upon DO.

As a second stage, we expanded the potential dependent variables to include all environmental conditions, geomorphic, and hydrologic variables. Results were even more highly successful than with environmental variables alone. Example resultant models are listed below.

$$\begin{aligned}\text{DO (mgL}^{-1}\text{, lowest 5\% metric)} = {} & 4.29 - 0.108\,(\text{Relative Runoff}) + 0.46\,(\text{Tidal Range}) \\ & + 56.7\,(\text{Runoff/Tidal exchange ratio}) + 0.04\,(S) \\ & (r^2 = 0.70;\ \text{Prob}>F=0.0013);\end{aligned}$$

$$\begin{aligned}\text{DO (mgL}^{-1}\text{, low tide September bottom)} = {} & 6.66 - 0.029\,(\text{Relative Runoff}) \\ & + 0.34\,(\text{Tidal Range}) \\ & (r^2 = 0.80;\ \text{Prob}>F=0.0001);\end{aligned}$$

$$\begin{aligned}\text{DO (\% saturation, low tide September bottom)} = {} & 43.1 - 0.367\,(\text{Relative Runoff}) \\ & + 4.07\,(\text{Tidal Range}) \\ & + 2.51\,(T) \\ & (r^2 = 0.84;\ \text{Prob}>F=0.0001);\end{aligned}$$

For all metrics tested, the relative runoff variable had the highest partial correlation coefficient and explained the highest variability in the dependent variable. Interestingly, size per se or environmental variables were less selected in the stepwise regression procedures and seemed to explain relatively low amounts of system-to-system DO variability. We feel the model results are sufficient evidence that confirms a principal difference related to the Little River system. As shown, it has higher relative freshwater runoff and this is reflected in generally lower salinity.

Secondarily, Little River has lower tidal range, but those downeast systems with high tidal range are well captured in the model through a positive influence of greater tidal range upon DO concentrations. The generality of these model results thus may be high not only for Little River, but for the systems in this data set, as judged by the high r^2 and thus the amount of variability explained by the regression. The general use of these empirical models, and the concept behind them, should be further explored and tested against other Maine estuaries and embayments.

CONCLUSIONS

DO Ranges

For the most part, the systems studied did not have low measured DO conditions and the variability to be explained does not include systems that have DO problems. Obviously, results show that DO varies with factors like time of year, time of day, depth, T, S.

Comment on Sampling Strategy

The approach taken by field efforts was to sample systems, as much as practical, at low tide near the beginning of the day. This represented an effort to detect the lowest DO conditions of the day. Results showed that for July and September measurements, samples taken at this time were lower than those taken later in the day. The strategy mixes the potential effect of low tide and nighttime respiration (early in the day sampling) vs. high tide and daytime primary production (in the afternoon). Regardless, the lowest events would seem to be captured by this sampling strategy.

Study Design: Systems for Study

The simple 3 by 3 flushing/loading study design was imperfect. The conceptual model implied by this simple design was not directly supported, perhaps in part because the characterization of relative loading could be improved. We believe that flushing is high in most of these systems to maintain relatively high DO by physical mixing. However, where there was more substantial runoff, possible stratification, and lower salinity, (and possibly high loading), DO was low. Thus, it is suggested that additional effort might examine other systems with some of these attributes to further examine the empirical models that were successfully developed with the current data set.

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Table 1. Geomorphometric, hydrologic, and loading information for selected study areas.

	Region	HW Area (km2)	CD Area (km2)	HW Volume (millions m3)	Tidal Volume (millions m3)	Flushing Time (hrs)	Perimeter (km)	Length (m)	Width (m)	Max. Depth (m)	Cross Section Area (mouth, m2)	Mean Tidal Range (m)	Watershed Area (km2)	Annual W. s. runoff (millions m3)	Loading (relative units)
Spruce Creek	S	2.0	0.62	4.5	3.3	10	16.9	3267	555	6.7	942	2.7	24.3	13.6	2
Cape Neddick Harbor	S	0.3	0.20	1.25	0.7	17	2.9	732	427	9.8	3587	2.6	27.8	15.6	2
Little River	S	0.7	0.15	1.1	1.0	5	5.2	1085	780	2.4	167	2.6	112.4	62.9	2
Biddeford Pool	S	2.0	0.14	2.51	2.3	5	8.2	1905	620	5.2	335	2.7	2.3	1.3	2
Fore River	Ca	5.3	2.79	26.7	11.1	23	26.8	7473	737	12.2	10627	2.8	134.9	75.6	3
Back Cove	Ca	2.2	0.35	4.2	3.1	9	7.6	2256	1549	7.6	2162	2.8	11.3	6.3	2
Harraseeket River	Ca	4.6	1.63	11.9	8.2	11	29.1	6066	1057	18.9	2230	2.7	19.3	10.8	2
Maquoit Bay	Ca	10.2	7.29	40.4	23.9	14	23.4	5903	2113	7.3	12425	2.8	16	9.0	2
Mere Point Bay	Ca	3.5	1.81	11.8	7.2	13	15.7	5740	986	6.1	4563	2.7	5.537	3.1	2
Middle Bay	Ca	10.4	7.20	49.8	24.3	19	18.6	6645	1595	13.7	15261	2.7	4	2.2	2
Quahog Bay	Ca	7.0	5.94	50.3	17.3	27	30.6	4978	732	21.0	8158	2.7	6.7	3.8	2
New Meadows River	Ca	18.2	15.10	194	45.2	47	46.1	13228	1118	46.9	24173	2.7	27.6	15.4	2
Boothbay Harbor	M	2.1	1.97	18.7	5.4	36	11.6	1833	1063	14.6	12554	2.7	4.6	2.6	2
Linekin Bay	M	6.5	6.17	86.8	17.0	57	15.6	4398	1297	32.3	19746	2.7	6.7	3.7	1
Union River Bay	B	32.8	30.70	553	101.0	62	38.9	10680	2359	60.0	77149	3.2	1458	817.0	2
Somes Sound	B	8.1	7.00	116	23.5	55	20.8	6939	894	47.5	6443	3.1	37.3	20.9	2
Taunton Bay	B	13.6	8.02	52.5	34.2	12	46.5	11227	2012	23.2	1208	3.2	157.7	88.3	2
Pleasant River	E	8.5	3.43	29.7	19.9	11	41.0	12476	711	12.2	6783	3.4	326.3	183.0	1
Whiting Bay	Co	9.1	5.68	62.9	39.3	13	41.2	6807	1057	13.4	13067	5.4	166.1	93.0	1

Data provided by ME DEP

Table 2. Dissolved oxygen metrics (both [DO] mgL^{-1} and %SAT) for selected study areas.

	Minimum [DO]	Minimum %SAT	Lowest 5% n	Mean Lowest 5% [DO]	Mean Lowest 5% %SAT	Low Tide Sept Bot n	Mean Low Tide Sept Bot [DO]	Mean Low Tide Sept Bot %SAT	Mean n	Mean [DO]	Mean %SAT
Spruce Creek	4.49	54.4	42	6.37	80.4	32	6.78	82.7	818	7.66	94.2
Cape Neddick Harbor	7.44	83.5	13	7.66	83.9				246	8.34	100.1
Little River	5.17	62.5	15	5.41	64.5	10	5.91	66.5	286	7.11	87.4
Biddeford Pool	6.94	88.1	12	7.00	88.4	3	7.54	89.4	185	8.13	97.4
Fore River	7.07	84.9	8	7.18	86.5	5	7.64	92.1	132	9.26	113.8
Back Cove	7.36	88.0	3	7.39	88.2	3	7.46	88.9	50	9.12	112.5
Harraseeket River	6.81	87.1	4	6.86	87.9	3	7.39	90.8	67	8.02	103.1
Maquoit Bay	6.84	92.2	4	7.01	92.5	4	7.91	98.8	69	8.47	110.4
Mere Point Bay	6.89	91.4	1	6.89	91.4	1	7.71	95.1	15	8.26	106.6
Middle Bay	6.38	85.0	3	6.60	86.1	3	7.53	92.9	55	8.38	107.7
Quahog Bay	5.99	70.6	6	6.18	73.7	5	8.00	97.6	111	8.17	102.1
New Meadows River	7.03	81.4	10	7.12	84.1	5	7.37	87.9	186	8.51	102.7
Boothbay Harbor	6.84	78.4	8	7.01	81.7				155	9.15	110.3
Linekin Bay	6.88	74.4	9	7.11	79.6				178	9.65	112.3
Union River Bay	6.72	74.1	7	6.95	80.2	1	7.84	91.9	123	8.55	102.3
Somes Sound	6.94	81.1	19	7.20	84.7	6	7.80	91.4	366	8.49	99.3
Taunton Bay	7.62	94.6	12	7.67	95.3	8	7.86	97.1	225	9.00	113.4
Pleasant River	6.42	77.6	9	6.56	79.3	5	7.65	89.4	171	8.28	98.4
Whiting Bay	7.93	92.7	10	8.09	93.9	5	8.37	97.3	173	9.14	105.7

Table 3a. Correlation coefficients between all geomorphic, hydrologic, and loading metrics.

	HW Area	CD Area	HW Volume	Tidal Volume	Flushing Time	Perimeter	Max. Depth	Length	Width	Cross Section Area (mouth)	Mean Tidal Range	Watershed Area	Annual W. s. runoff	Annual Tidal exchange	June FW Discharge	July FW Discharge	August FW Discharge	September FW Discharge	Loading
HW Area	1.00																		
CD Area	0.98	1.00																	
HW Volume	0.92	0.97	1.00																
Tidal Volume	0.98	0.97	0.94	1.00															
Flushing Time	0.59	0.68	0.71	0.59	1.00														
Perimeter	0.70	0.58	0.45	0.67	0.23	1.00													
Max. Depth	0.79	0.83	0.83	0.78	0.89	0.51	1.00												
Length	0.74	0.63	0.51	0.68	0.32	0.91	0.58	1.00											
Width	0.70	0.66	0.56	0.66	0.28	0.36	0.40	0.40	1.00										
Cross Section Area	0.88	0.93	0.96	0.90	0.69	0.38	0.73	0.43	0.58	1.00									
Mean Tidal Range	0.24	0.16	0.14	0.37	-0.06	0.51	0.08	0.31	0.09	0.13	1.00								
Watershed Area	0.80	0.82	0.89	0.84	0.42	0.39	0.57	0.42	0.50	0.88	0.22	1.00							
Annual W. s. runoff	0.80	0.82	0.89	0.84	0.42	0.39	0.57	0.42	0.50	0.88	0.22	1.00	1.00						
Annual Tidal exchange	0.98	0.97	0.94	1.00	0.59	0.67	0.78	0.68	0.66	0.90	0.37	0.84	0.84	1.00					
June FW Discharge	0.80	0.82	0.90	0.84	0.43	0.38	0.57	0.41	0.50	0.88	0.21	1.00	1.00	0.84	1.00				
July FW Discharge	0.80	0.82	0.89	0.84	0.43	0.38	0.57	0.41	0.50	0.88	0.21	1.00	1.00	0.84	1.00	1.00			
August FW Discharge	0.80	0.83	0.90	0.84	0.44	0.37	0.58	0.40	0.51	0.89	0.20	1.00	1.00	0.84	1.00	1.00	1.00		
September FW Discharge	0.80	0.82	0.89	0.84	0.43	0.38	0.57	0.41	0.50	0.88	0.21	1.00	1.00	0.84	1.00	1.00	1.00	1.00	
Loading	-0.05	-0.02	-0.01	-0.12	-0.07	-0.21	-0.08	-0.14	-0.01	-0.04	-0.54	-0.04	-0.04	-0.12	-0.03	-0.03	-0.02	-0.03	1.00

Table 3b. Correlation coefficients between selected geomorphic, hydrologic, and dissolved oxygen metrics.

	CD Area	Flushing Time	Perimeter	Max. Depth	Width	Cross Section Area (mouth)	Mean Tidal Range	Watershed Area	Minimum [DO]	Minimum %SAT	Lowest 5% [DO]	Lowest 5% %SAT	Low Tide Sept Bot [DO]	Low Tide Sept Bot %SAT	Mean [DO]	Mean %SAT
CD Area	1.00															
Flushing Time	0.68	1.00														
Perimeter	0.58	0.23	1.00													
Max. Depth	0.83	0.89	0.51	1.00												
Width	0.66	0.28	0.36	0.40	1.00											
Cross Section Area (mouth)	0.93	0.69	0.38	0.73	0.58	1.00										
Mean Tidal Range	0.16	-0.06	0.51	0.08	0.09	0.13	1.00									
Watershed Area	0.82	0.42	0.39	0.57	0.50	0.88	0.22	1.00								
Minimum [DO]	0.14	0.13	0.26	0.19	0.29	0.10	0.41	0.02	1.00							
Minimum %SAT	-0.02	-0.18	0.21	-0.08	0.34	-0.11	0.30	-0.15	0.87	1.00						
Lowest 5% [DO]	0.11	0.13	0.25	0.19	0.23	0.08	0.49	0.01	0.88	0.71	1.00					
Lowest 5% %SAT	-0.01	-0.19	0.27	-0.07	0.35	-0.10	0.34	-0.14	0.70	0.85	0.79	1.00				
Low Tide Sept Bot [DO]	0.32	0.28	0.54	0.29	0.33	0.26	0.51	0.16	0.73	0.65	0.74	0.66	1.00			
Low Tide Sept Bot %SAT	0.24	0.18	0.47	0.18	0.38	0.16	0.31	0.03	0.64	0.67	0.67	0.73	0.95	1.00		
Mean [DO]	0.17	0.40	0.22	0.26	0.34	0.22	0.29	0.02	0.71	0.48	0.73	0.48	0.74	0.69	1.00	
Mean %SAT	0.10	0.17	0.19	0.07	0.51	0.10	0.06	-0.09	0.64	0.62	0.60	0.62	0.64	0.74	0.86	1.00

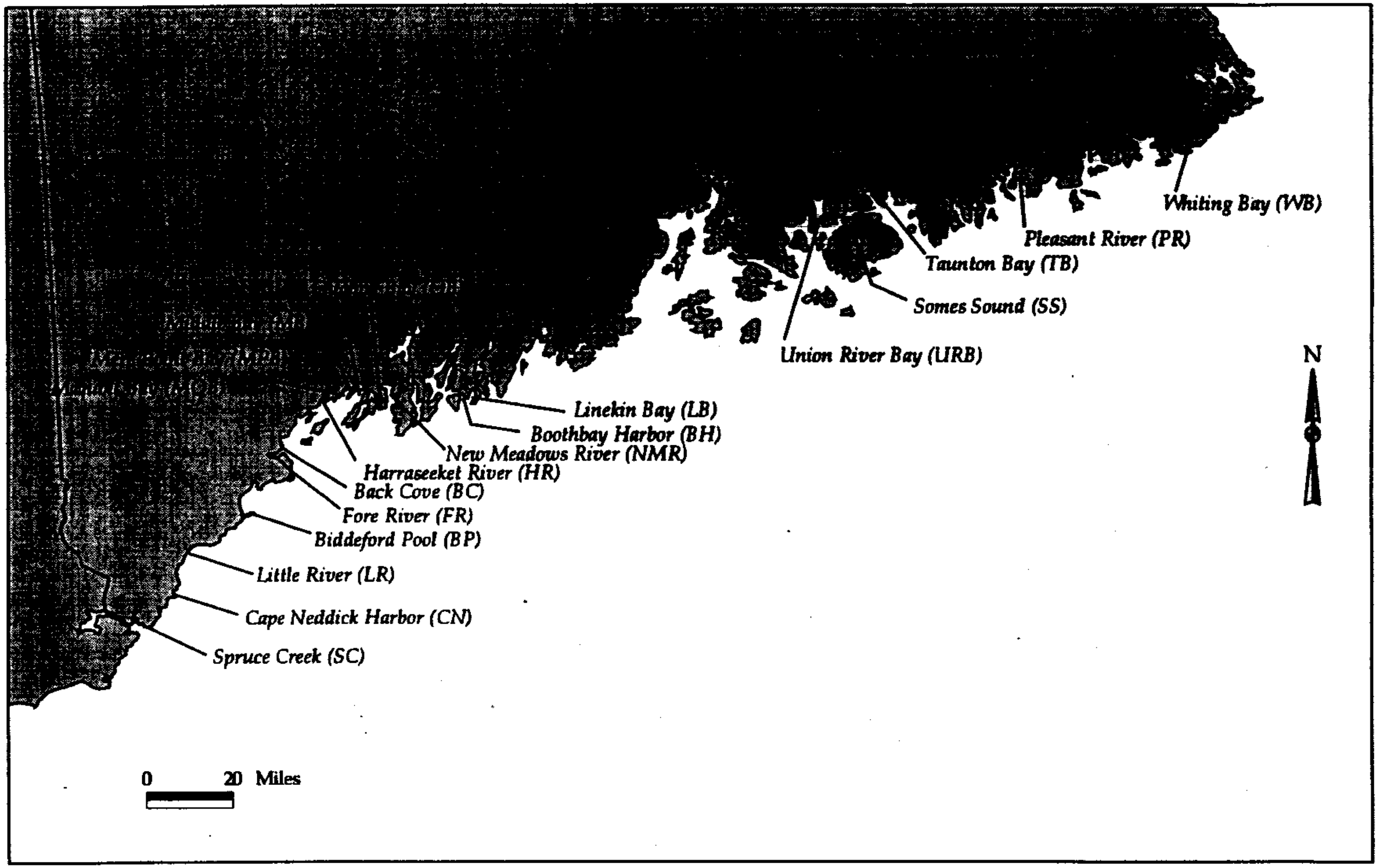


Figure 1. Maine Estuaries and Embayments: Selected Study Areas 1995

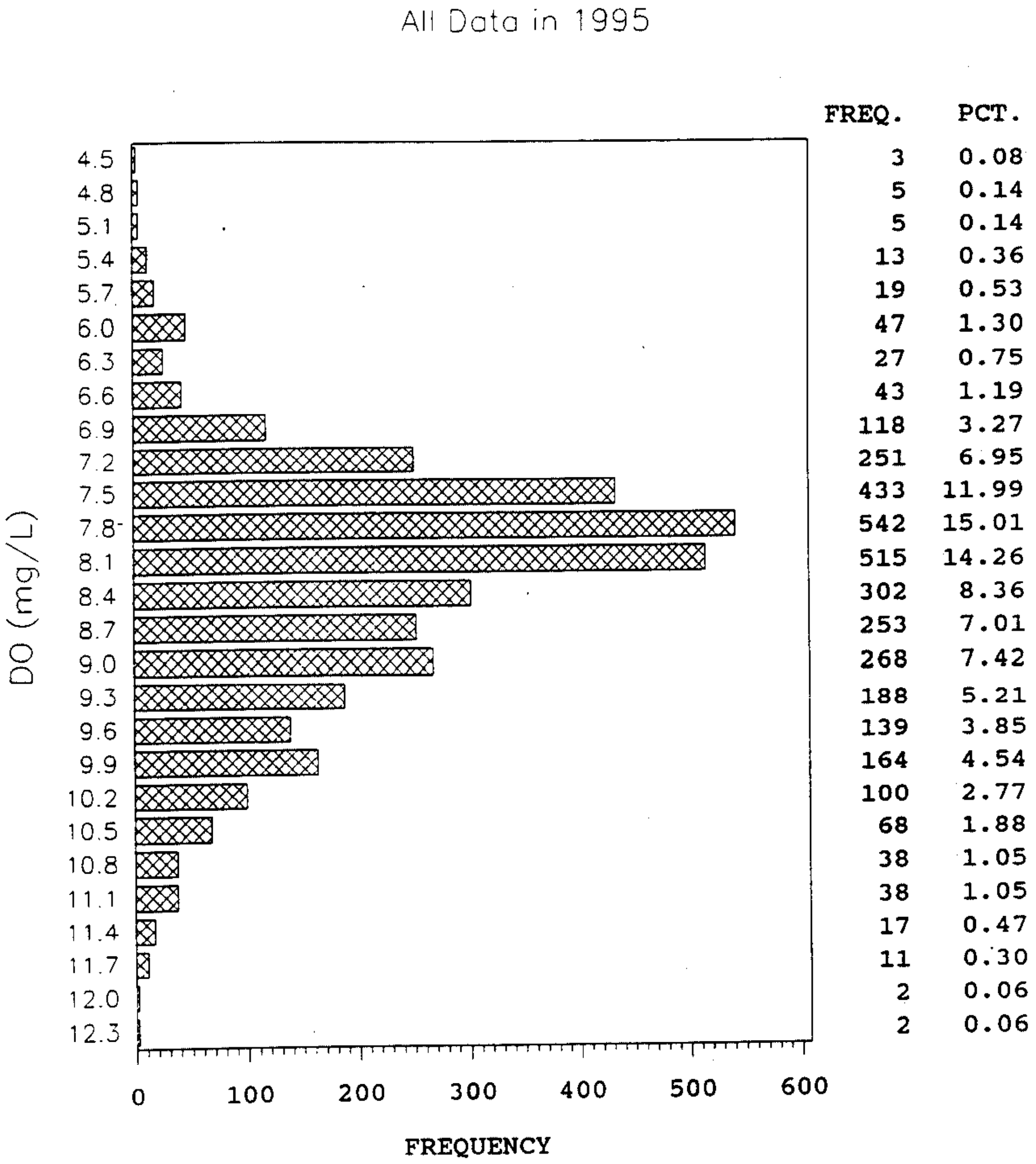
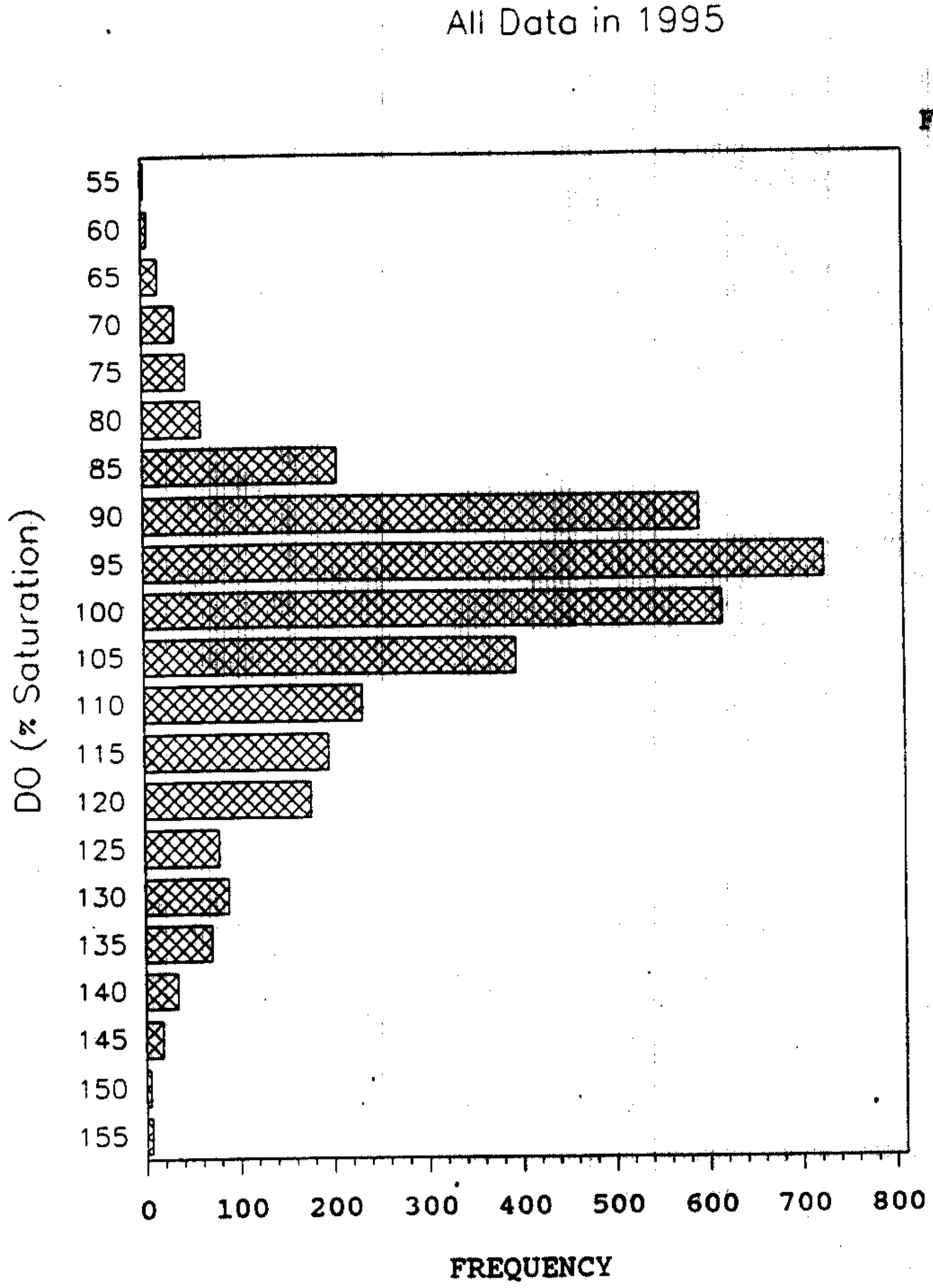


Figure 2. **Frequency distribution of all dissolved oxygen (mgL^{-1}) data in 1995.**



FREQ.	PCT.
3	0.08
6	0.17
17	0.47
35	0.97
46	1.27
62	1.72
207	5.73
592	16.39
725	20.08
616	17.06
395	10.94
232	6.42
196	5.43
177	4.90
79	2.19
89	2.46
71	1.97
34	0.94
18	0.50
5	0.14
6	0.17

Figure 3. Frequency distribution of all dissolved oxygen (%saturation) data in 1995.

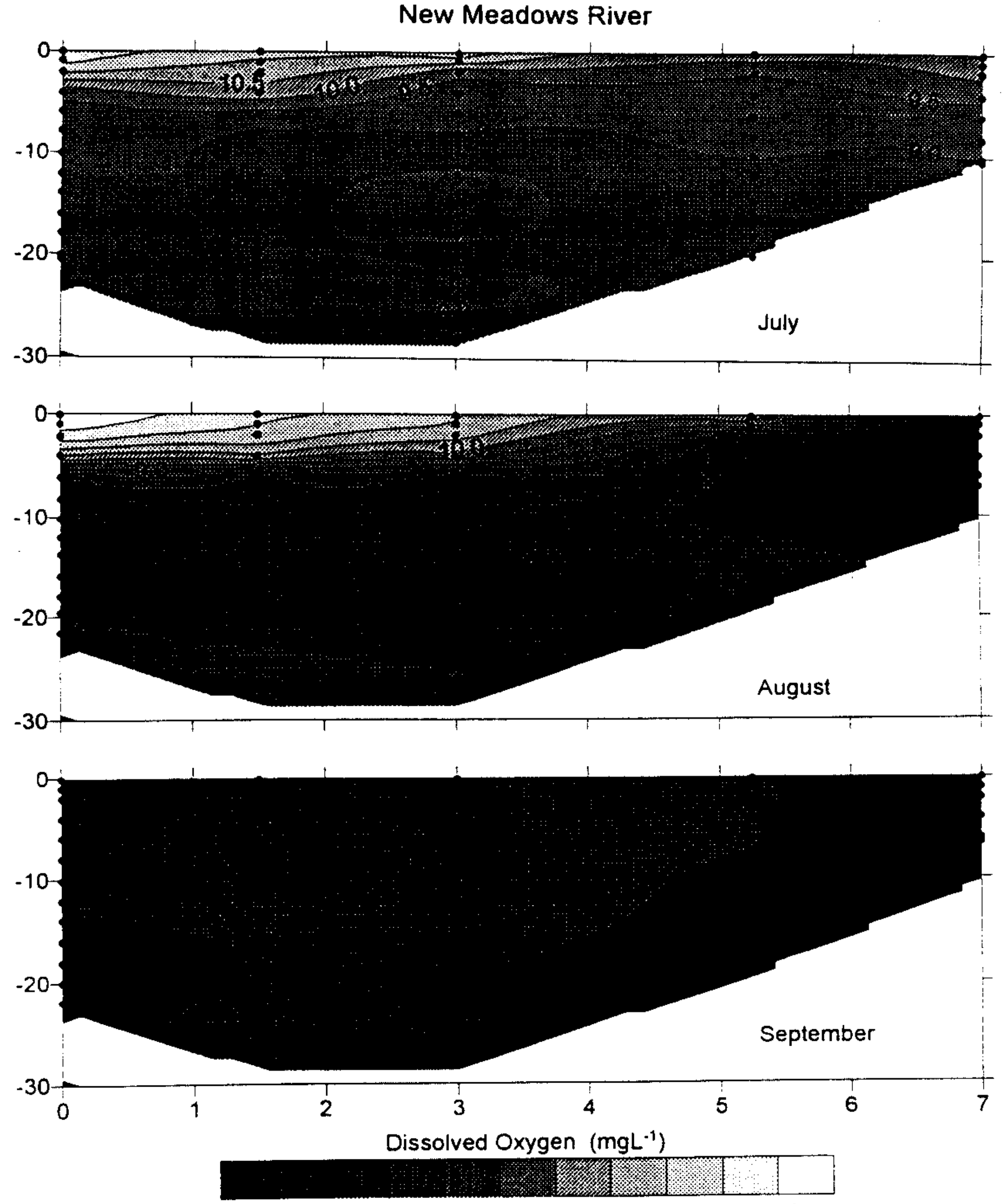


Figure 4a. Contours of dissolved oxygen (mgL^{-1}) data during flood tide in July and near low tide in August and September. Depth is in meters, the x-axis represents distance (miles) 'inshore' relative to the most seaward station, and the dots indicate sample depths.

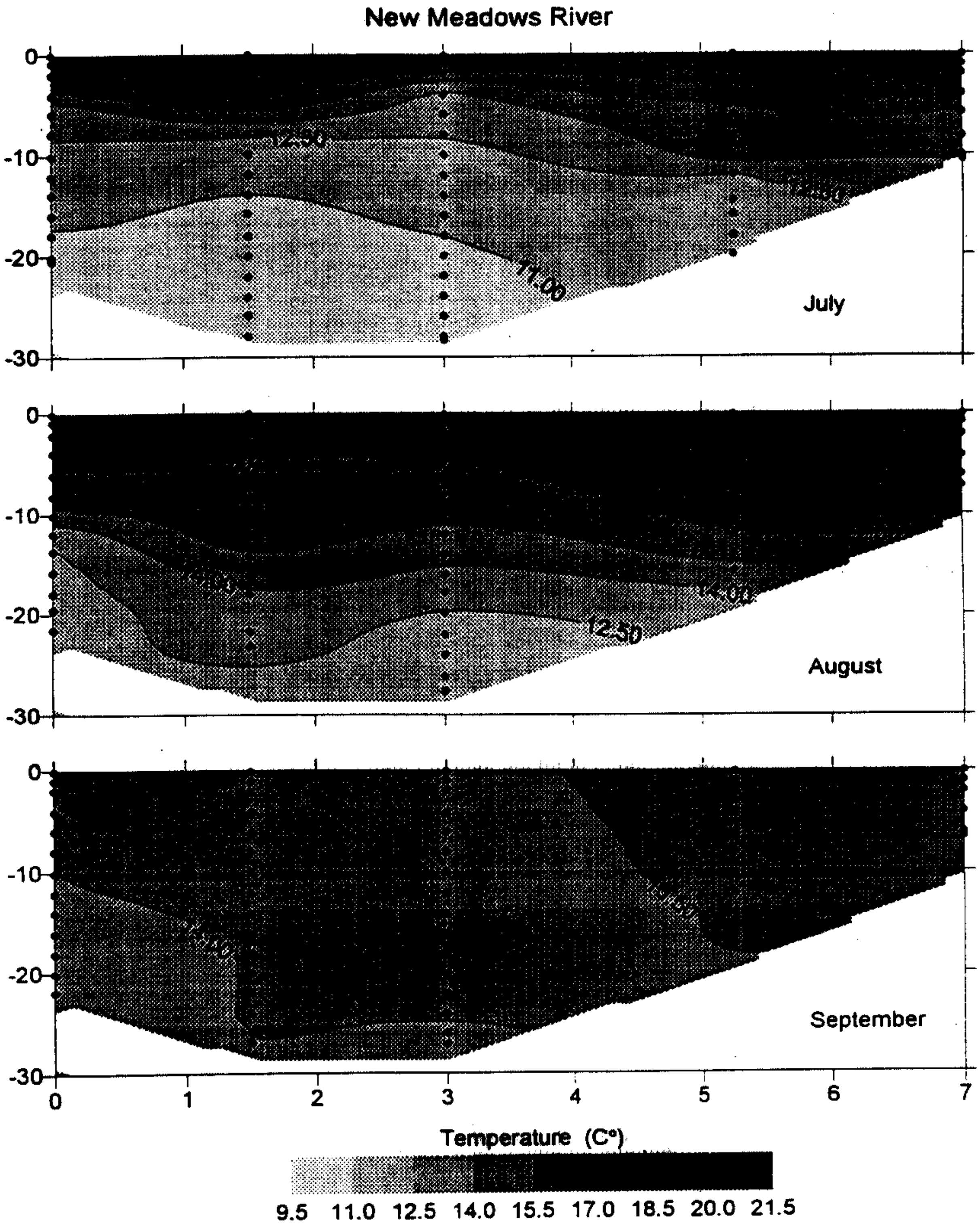


Figure 4b. Contours of temperature (C°) data during flood tide in July and near low tide in August and September. Depth is in meters, the x-axis represents distance (miles) 'inshore' relative to the most seaward station, and the dots indicate sample depths.

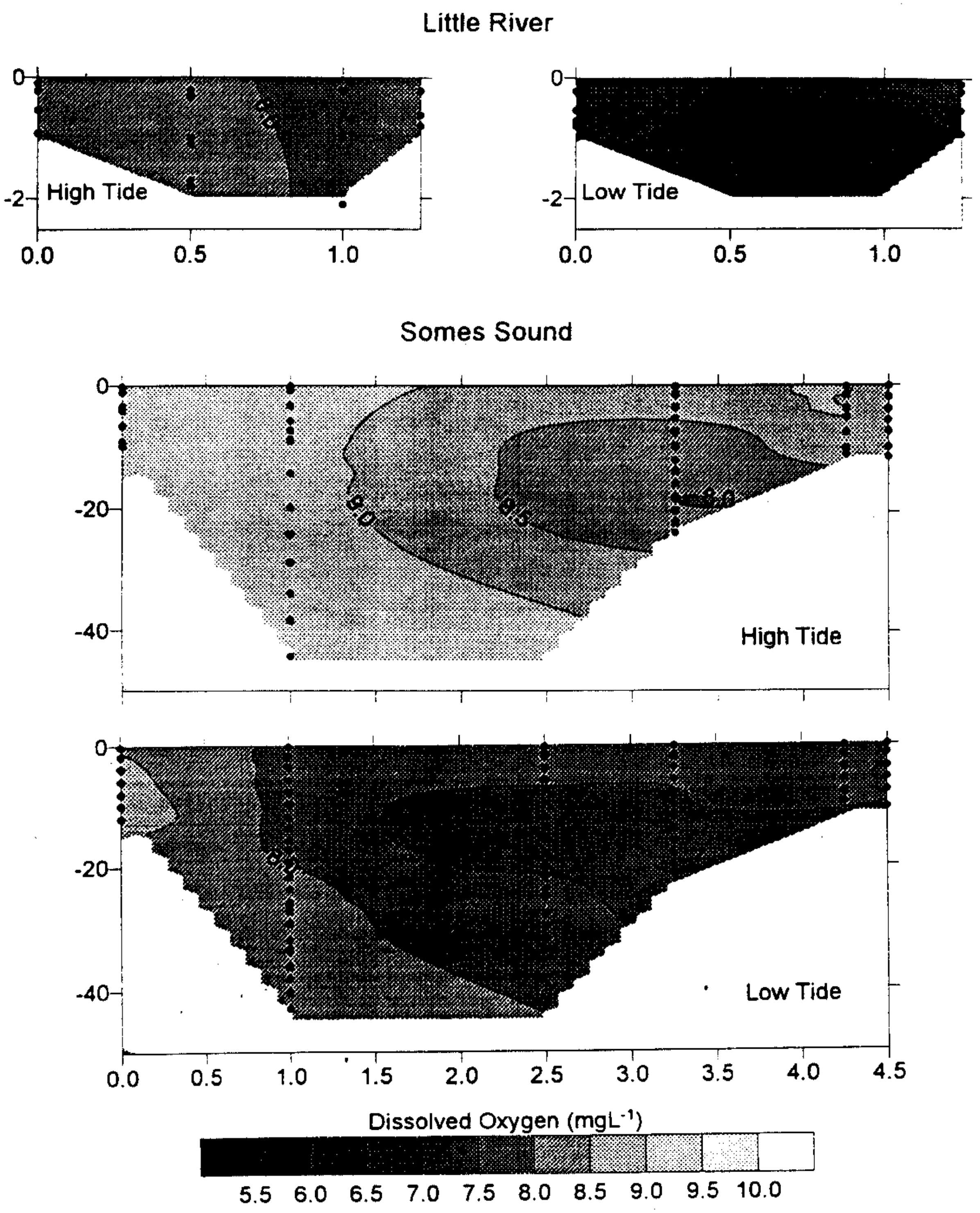
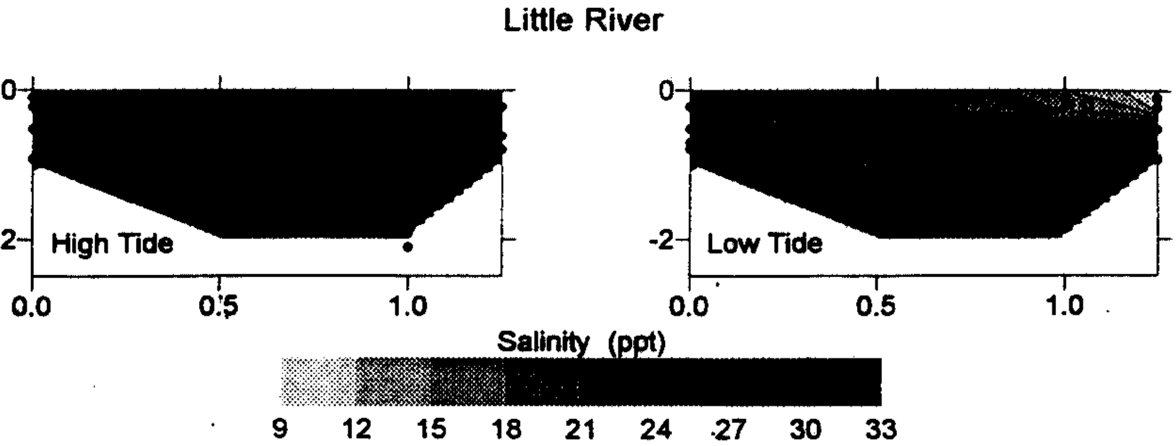


Figure 5a. Contours of dissolved oxygen (mgL^{-1}) data from high and low tides in September. Depth is in meters, the x-axis represents distance (miles) 'inshore' relative to the most seaward station, and the dots indicate sample dapth.



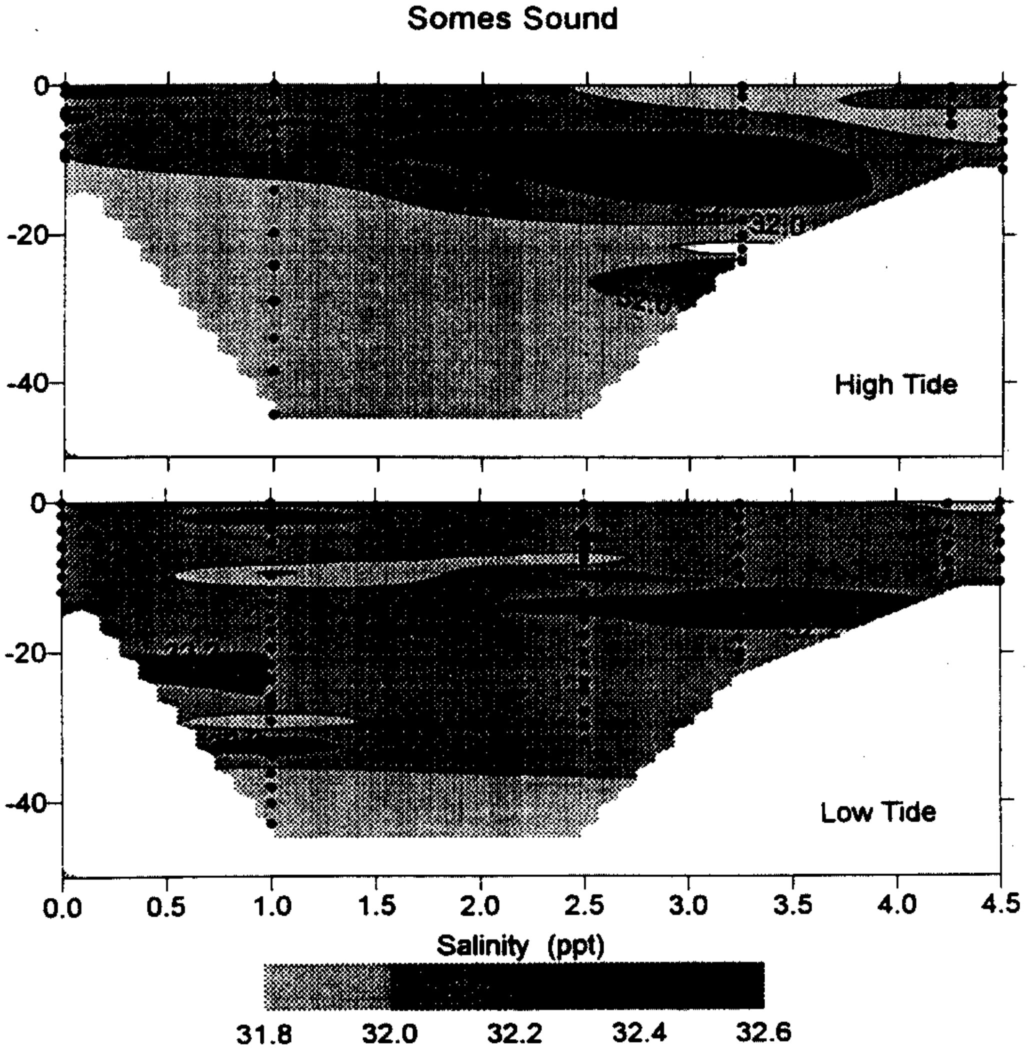


Figure 5b. Contours of salinity (ppt) data from high and low tides in September. Depth is in meters, the x-axis represents distance (miles) 'inshore' relative to the most seaward station, and the dots indicate sample depth.

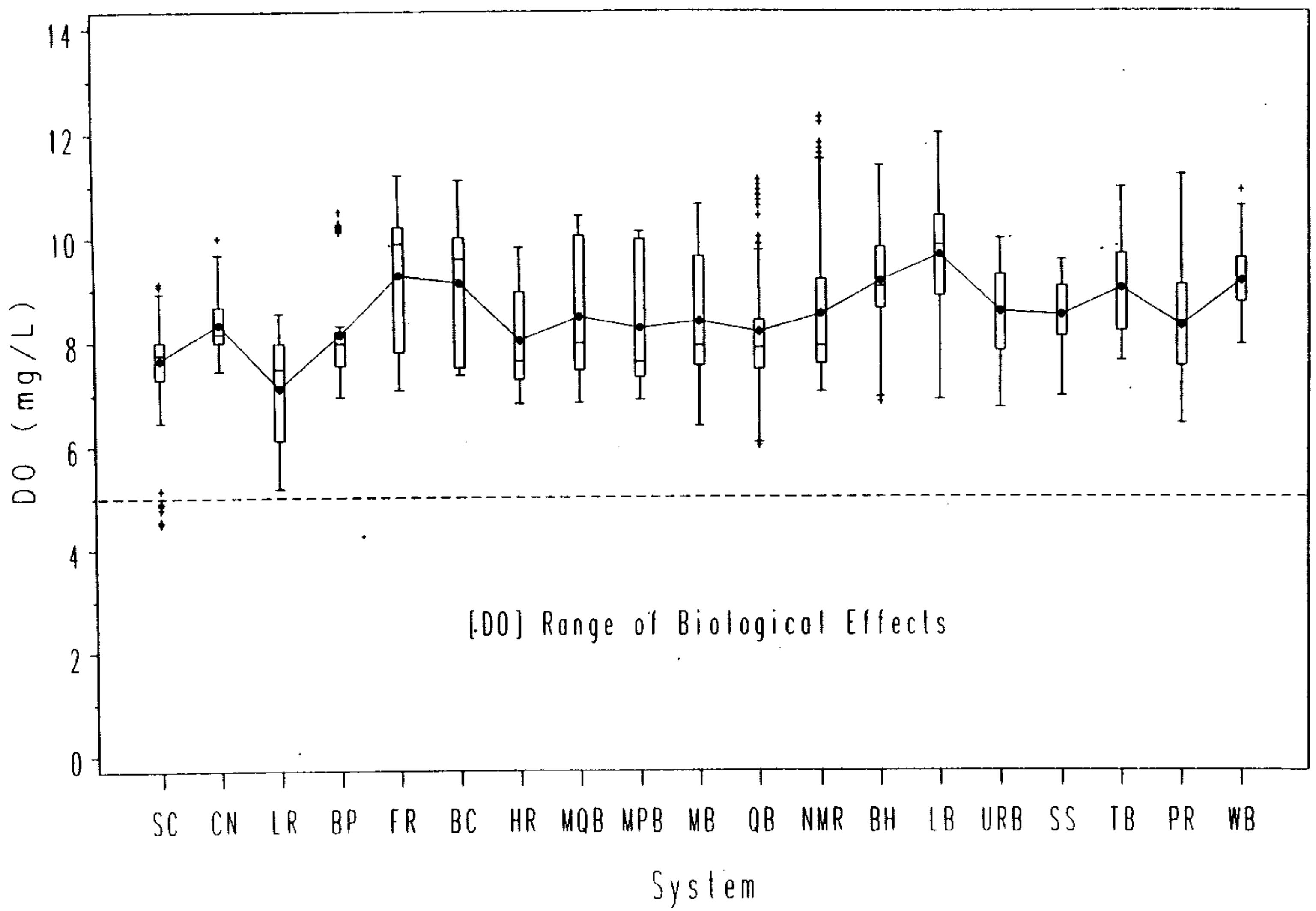


Figure 6a. Box and whisker plots of all dissolved oxygen (mgL^{-1}) data in 1995. Data are presented by system geographically from south to north. Mean values are shown by the connected dots. The dashed line at 5 mgL^{-1} indicates the DO level below which biological effects have been observed.

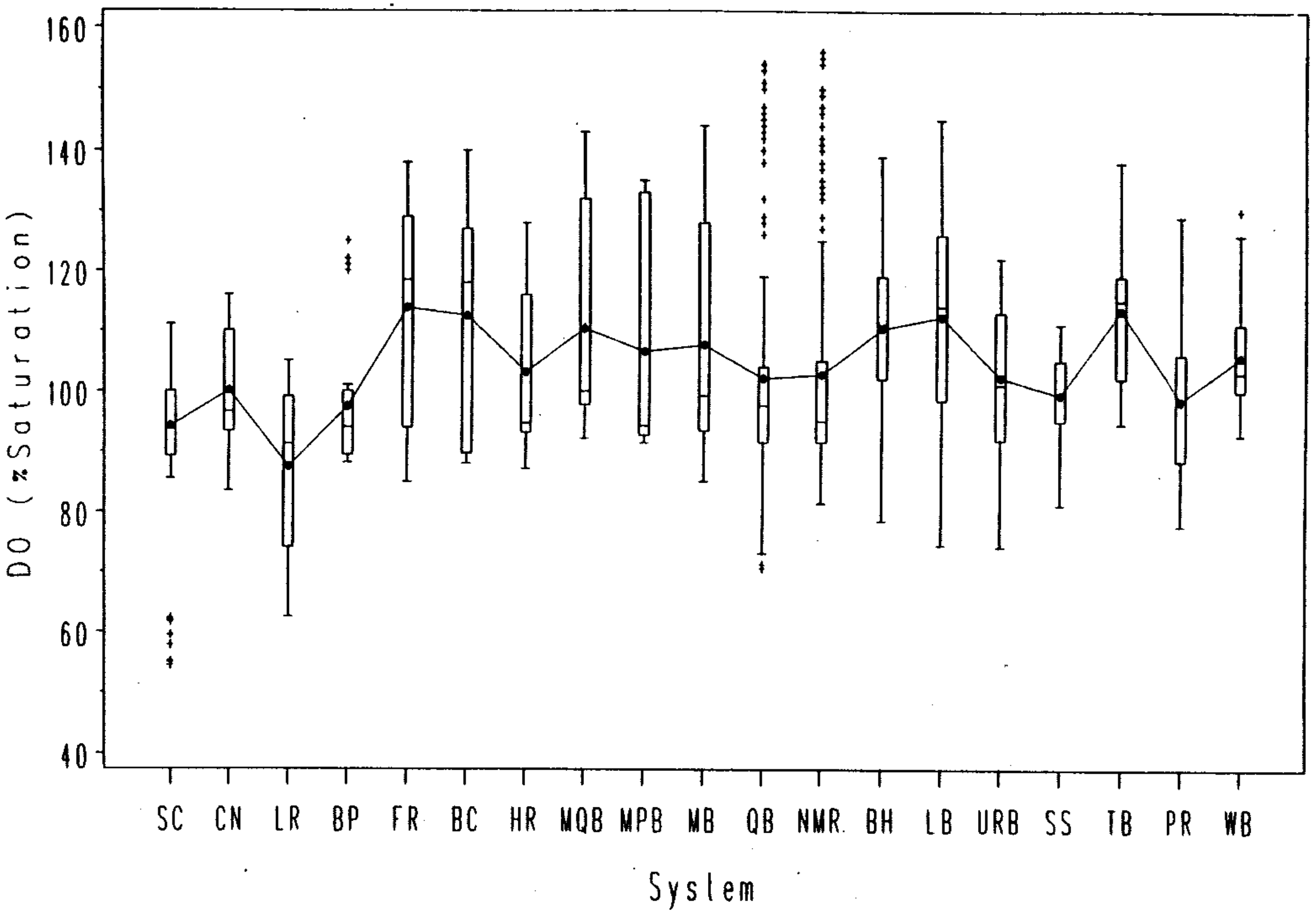


Figure 6b. Box and whisker plots of all dissolved oxygen (%saturation) data in 1995. Mean values are shown by the connected dots.

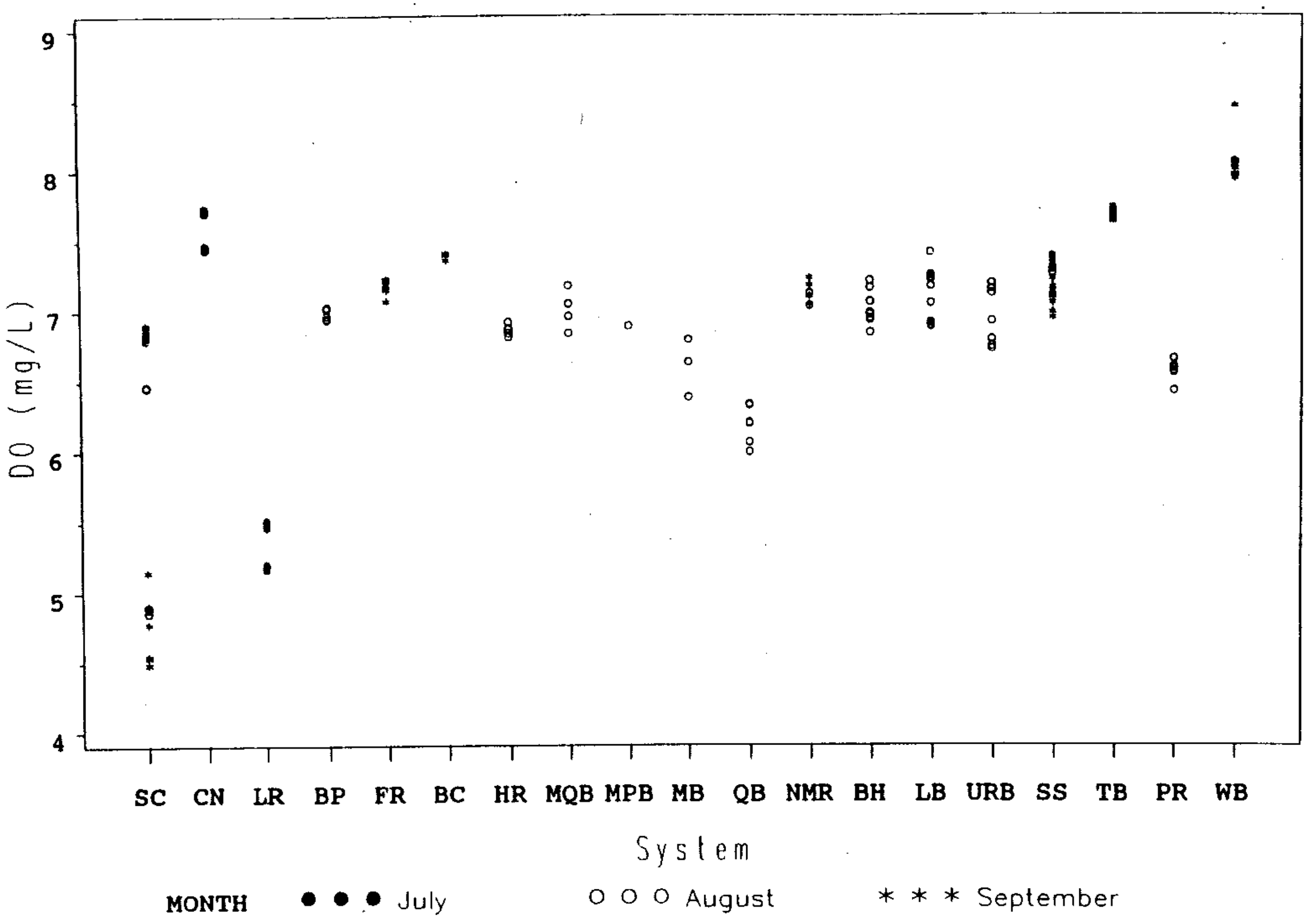


Figure 7a. The lowest 5% of dissolved oxygen (mgL^{-1}) data in each system. Symbols represent month in which samples were taken. (NOTE: Samples taken on 08/01/95 have been grouped with the July data.)

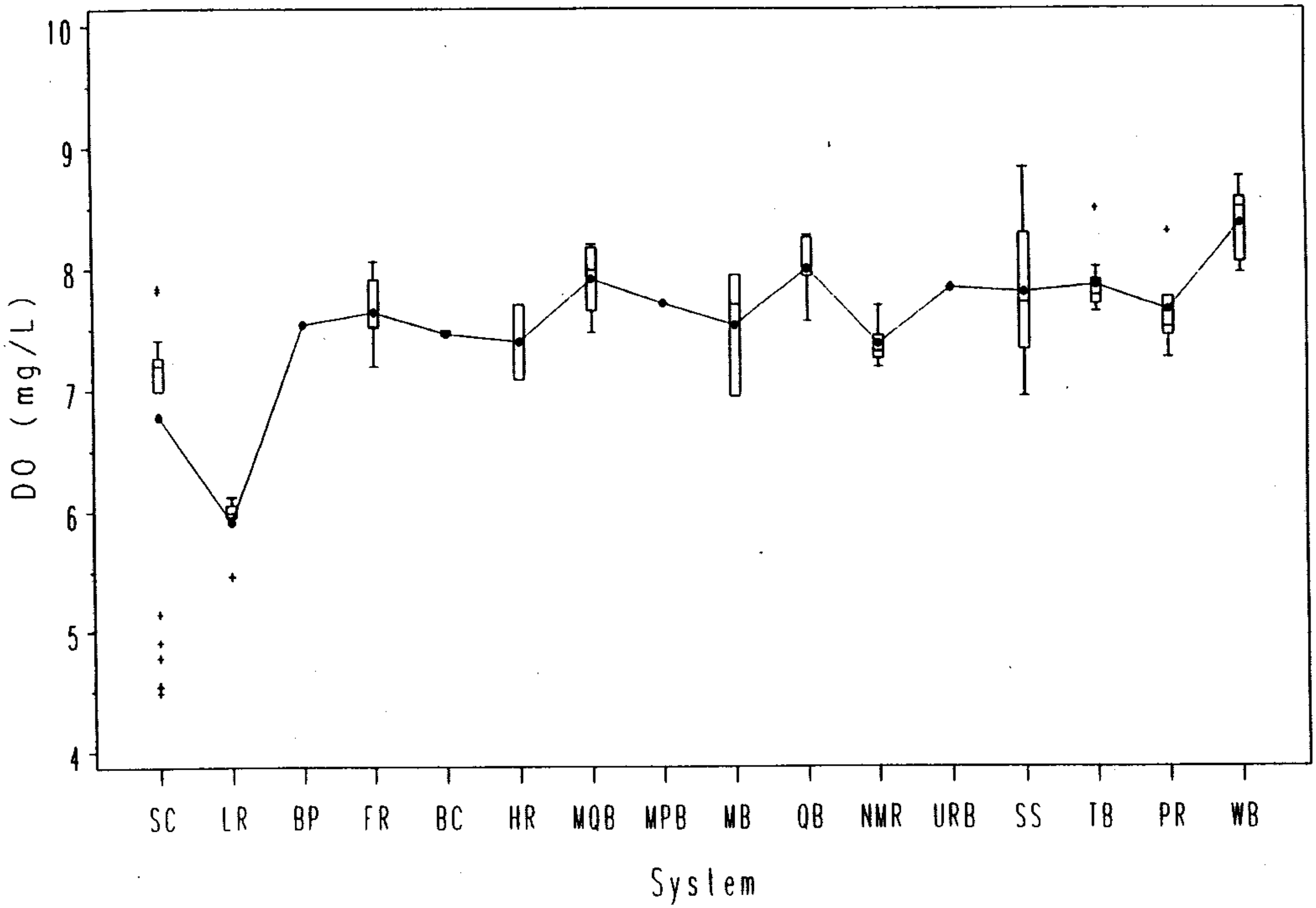


Figure 7b. Box and whisker plots of dissolved oxygen (mgL^{-1}) data for bottom water at low tide in September 1995. Mean values are shown by the connected dots. Boothbay Harbor and Linekin Bay were not sampled and Cape Neddick Harbor was only sampled at high tide in September.

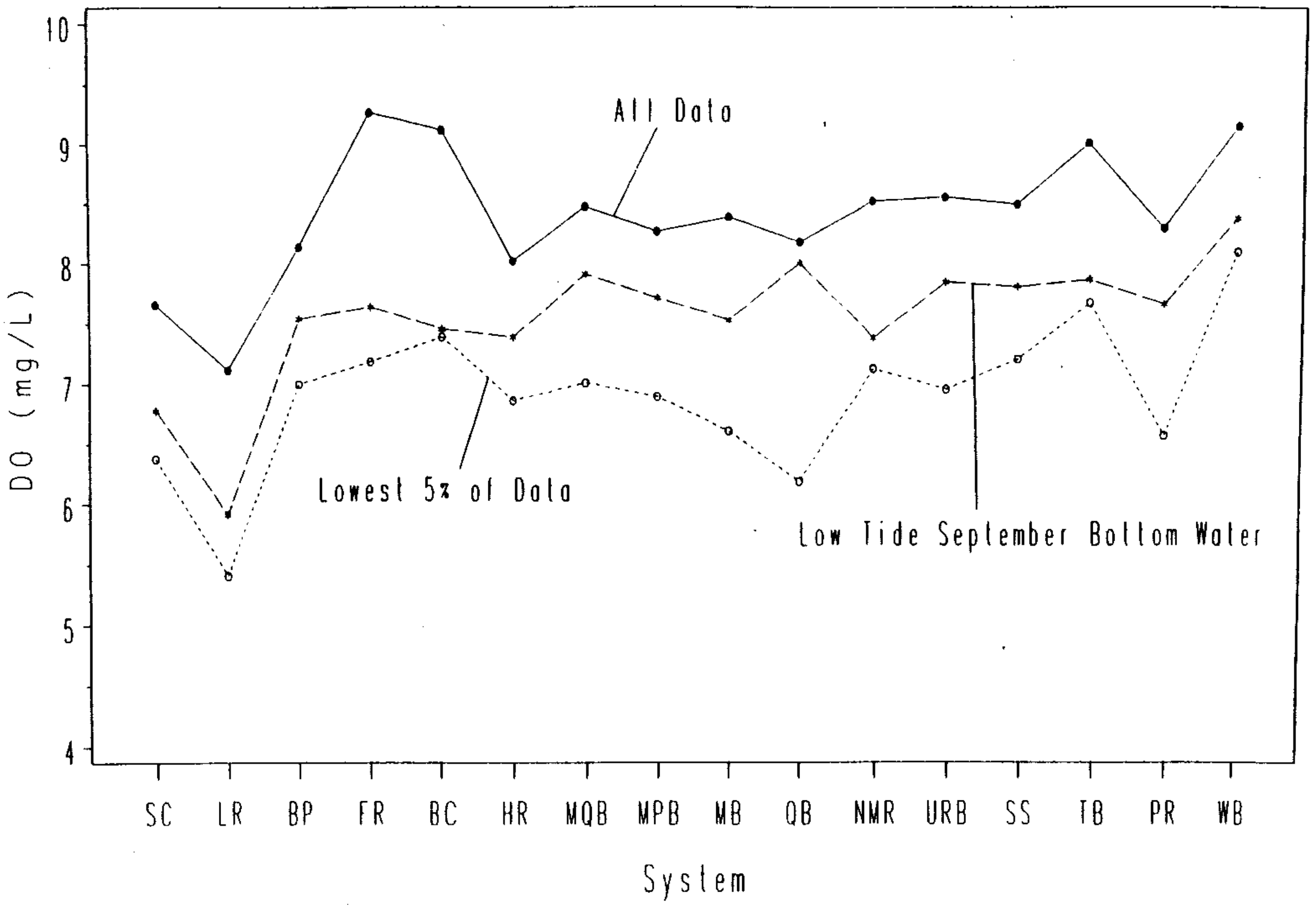


Figure 8. Mean dissolved oxygen values for all data, lowest 5% of data, and low tide September bottom water metrics.

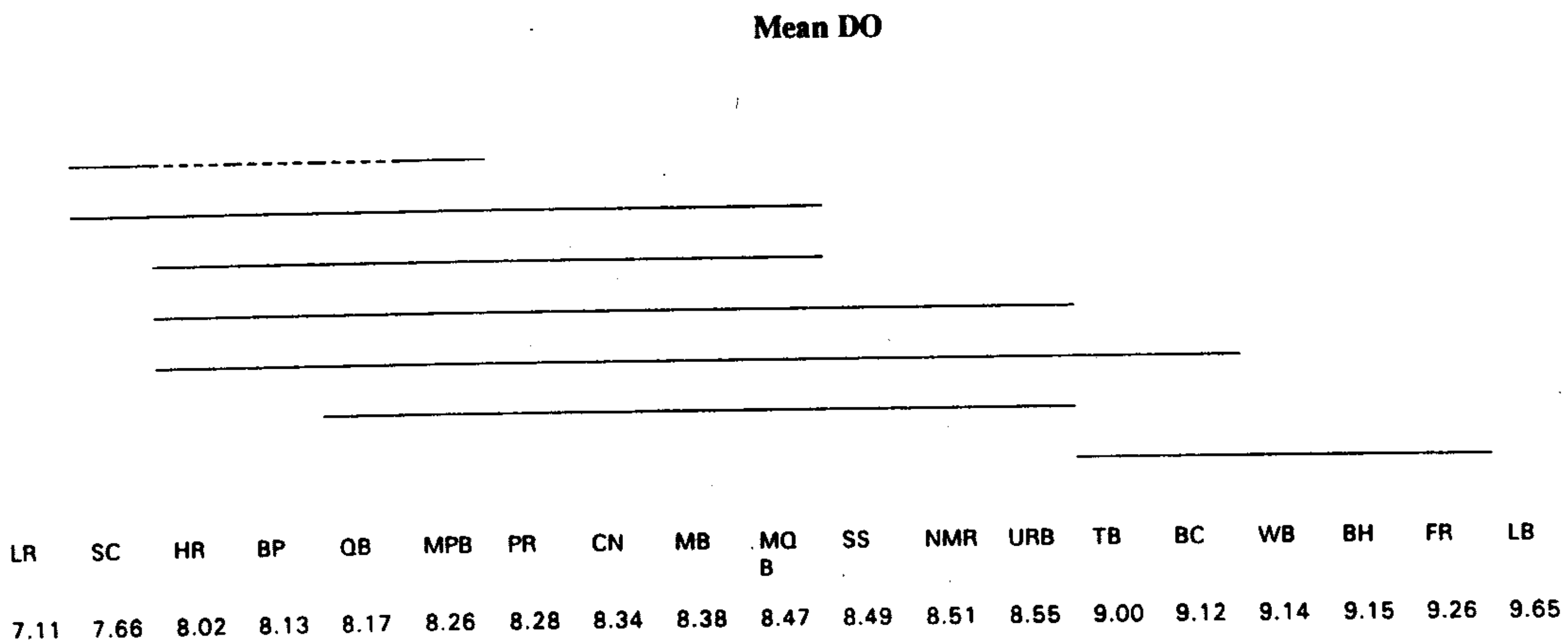
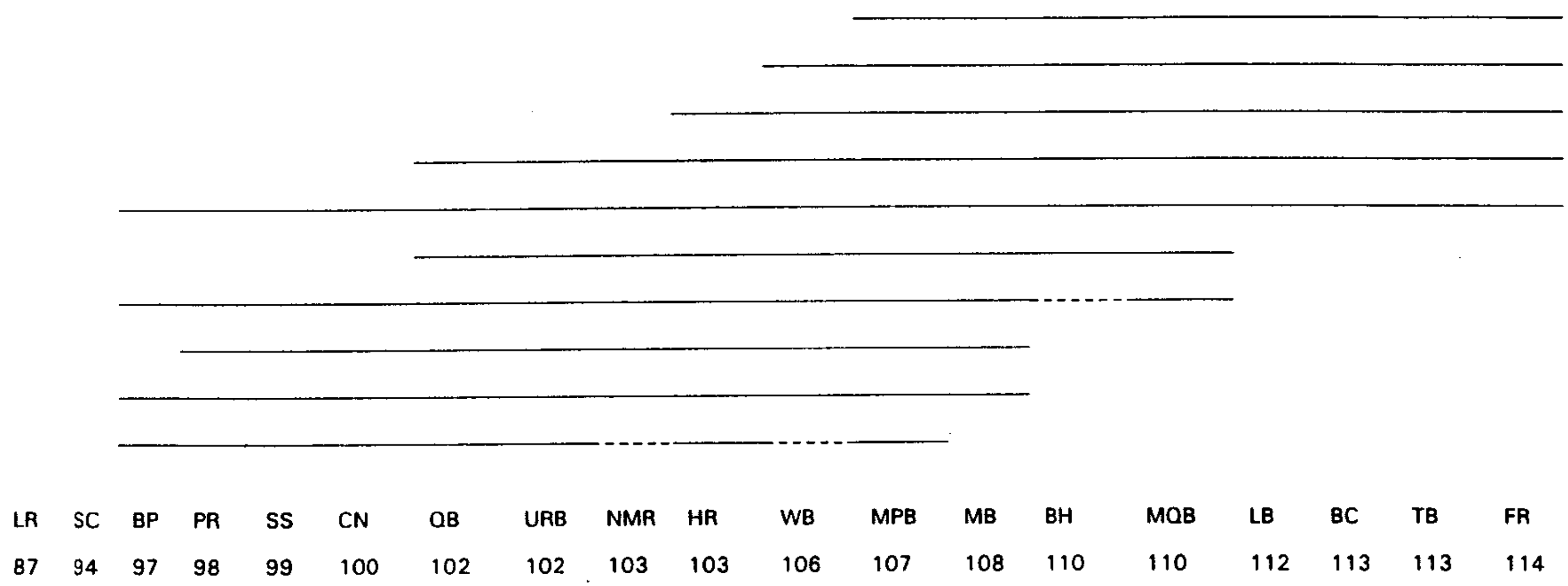


Figure 9a. Results of planned comparisons among systems with respect to the mean DO concentration. Codes for systems are given in Figure 1. Values are mg L^{-1}. Lines connect systems that are not significantly different; dotted lines show systems that are dissimilar for the given comparison.

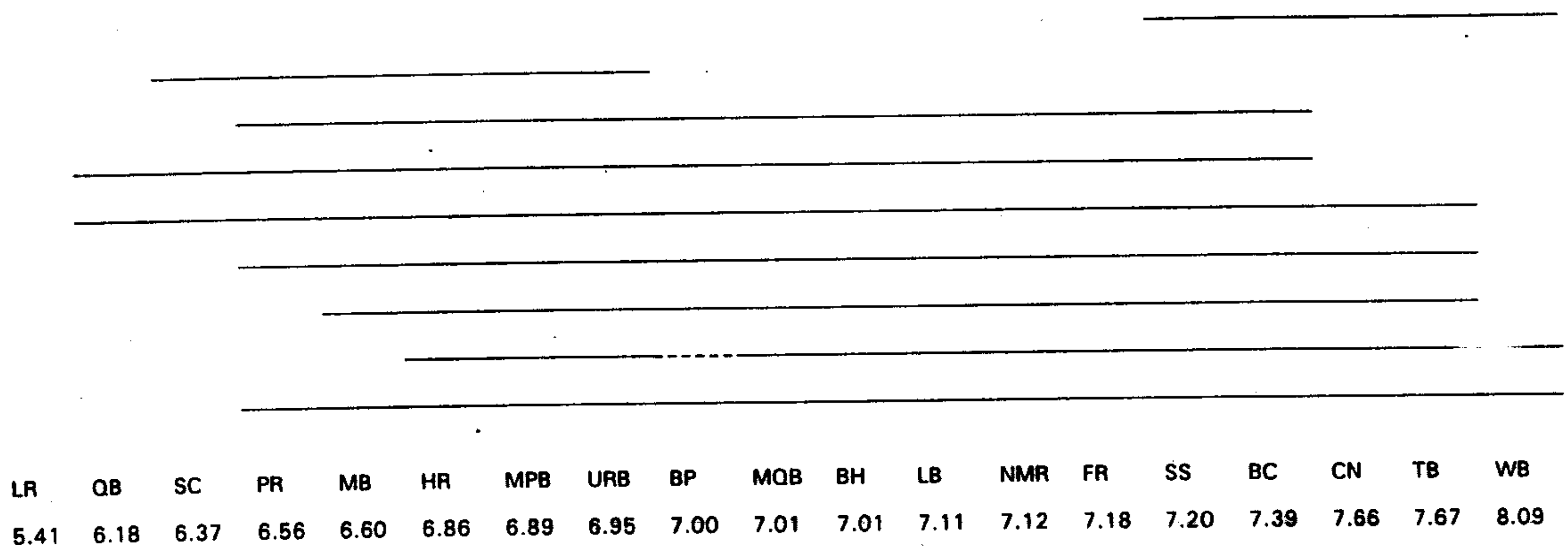
Mean % Saturation



Note: Results of planned comparisons have been slightly simplified for presentation.

Figure 9b. Results of planned comparisons among systems with respect to the mean % saturation. Codes for systems are given in Figure 1. Values are % saturation. Lines connect systems that are not significantly different; dotted lines show systems that are dissimilar for the given comparison.

Mean DO   Lowest 5% of Data



Note: Results of planned comparisons have been slightly simplified for presentation. For example, MPB was not different from other systems (due to a broad range) and for simplicity has been left out of comparisons illustrated here.

Figure 9c. **Results of planned comparisons among systems with respect to the mean DO concentration. Codes for systems are given in Figure 1. Values are mg L^{-1}. Lines connect systems that are not significantly different; dotted lines show systems that are dissimilar for the given comparison.**

Mean DO   Low Tide Bottom Water in September

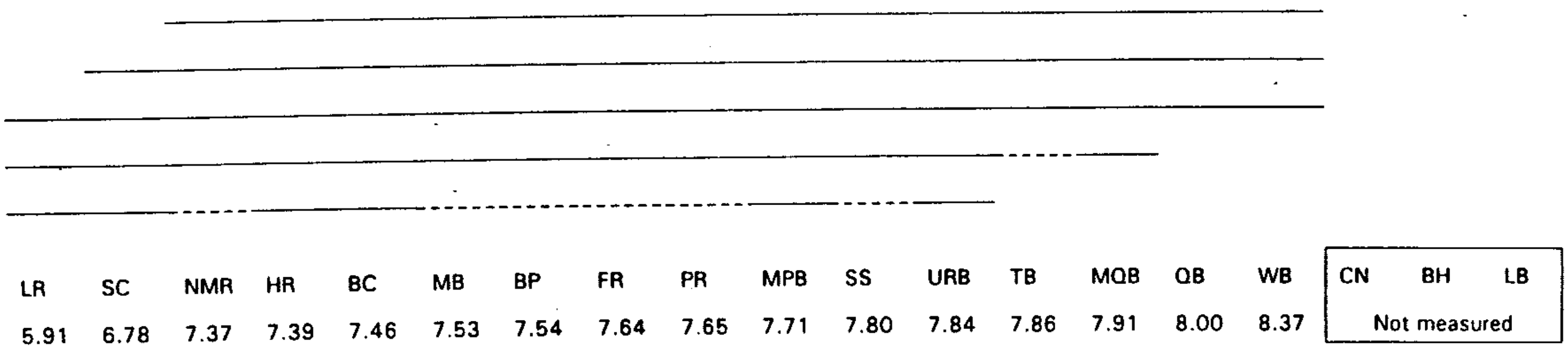


Figure 9d. Results of planned comparisons among systems with respect to the mean DO concentration. Codes for systems are given in Figure 1. Values are mg L^{-1}. Lines connect systems that are not significantly different; dotted lines show systems that are dissimilar for the given comparison.

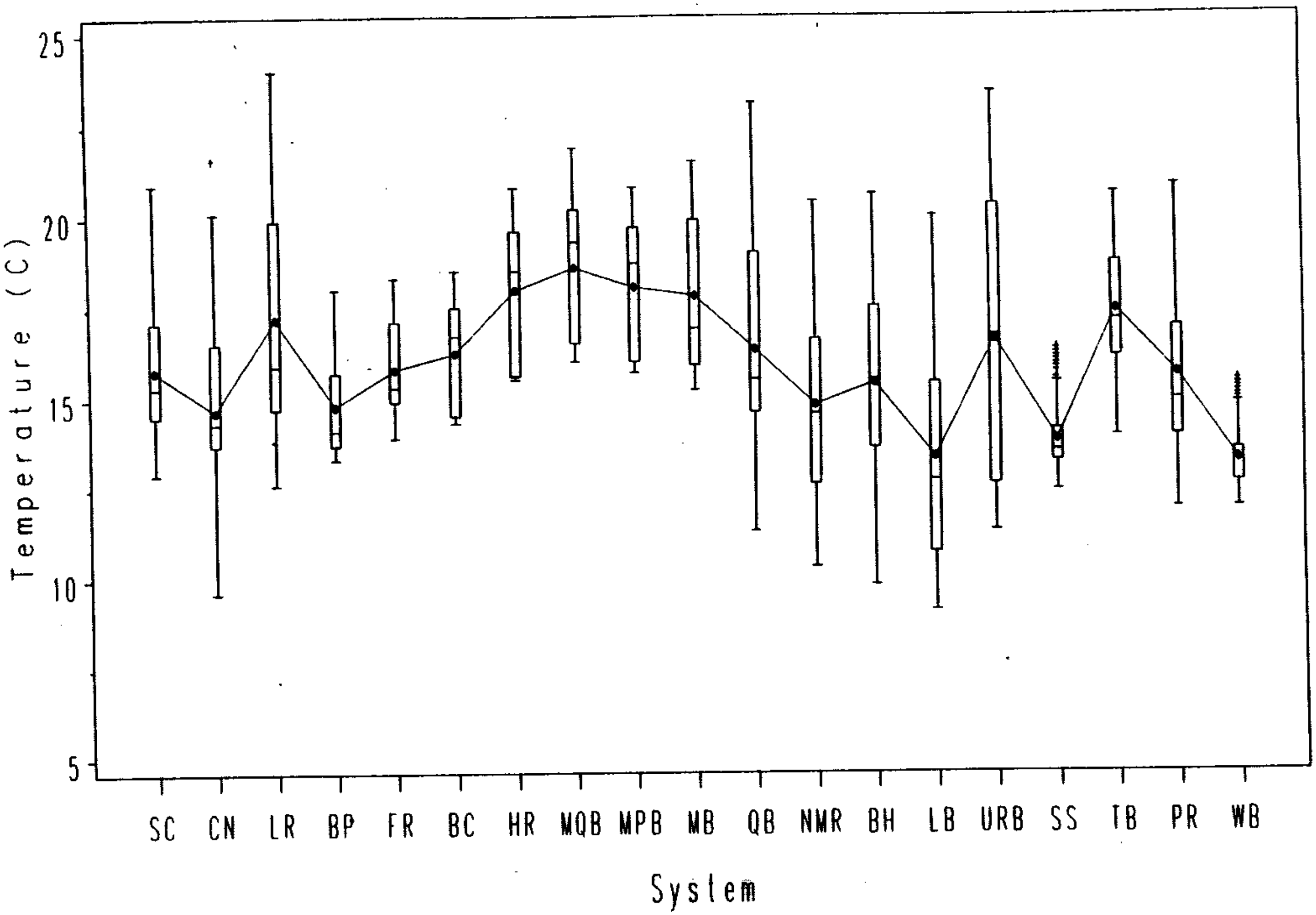


Figure 10a. Box and whisker plots for all Temperature (°C) data in 1995. Mean values are shown by the connected dots.

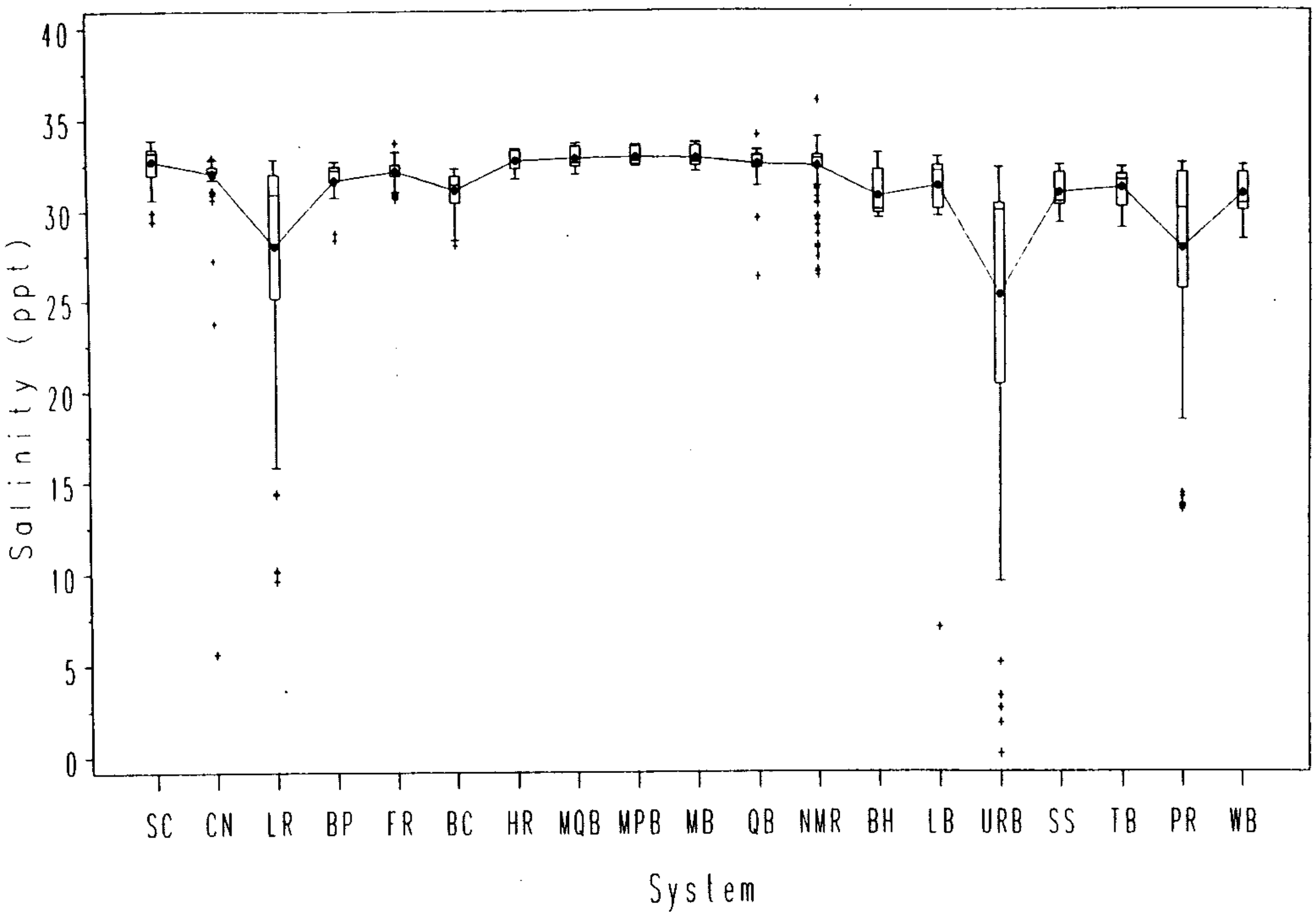


Figure 10b. Box and whisker plots for all salinity (ppt) data in 1995. Mean values are shown by the connected dots.

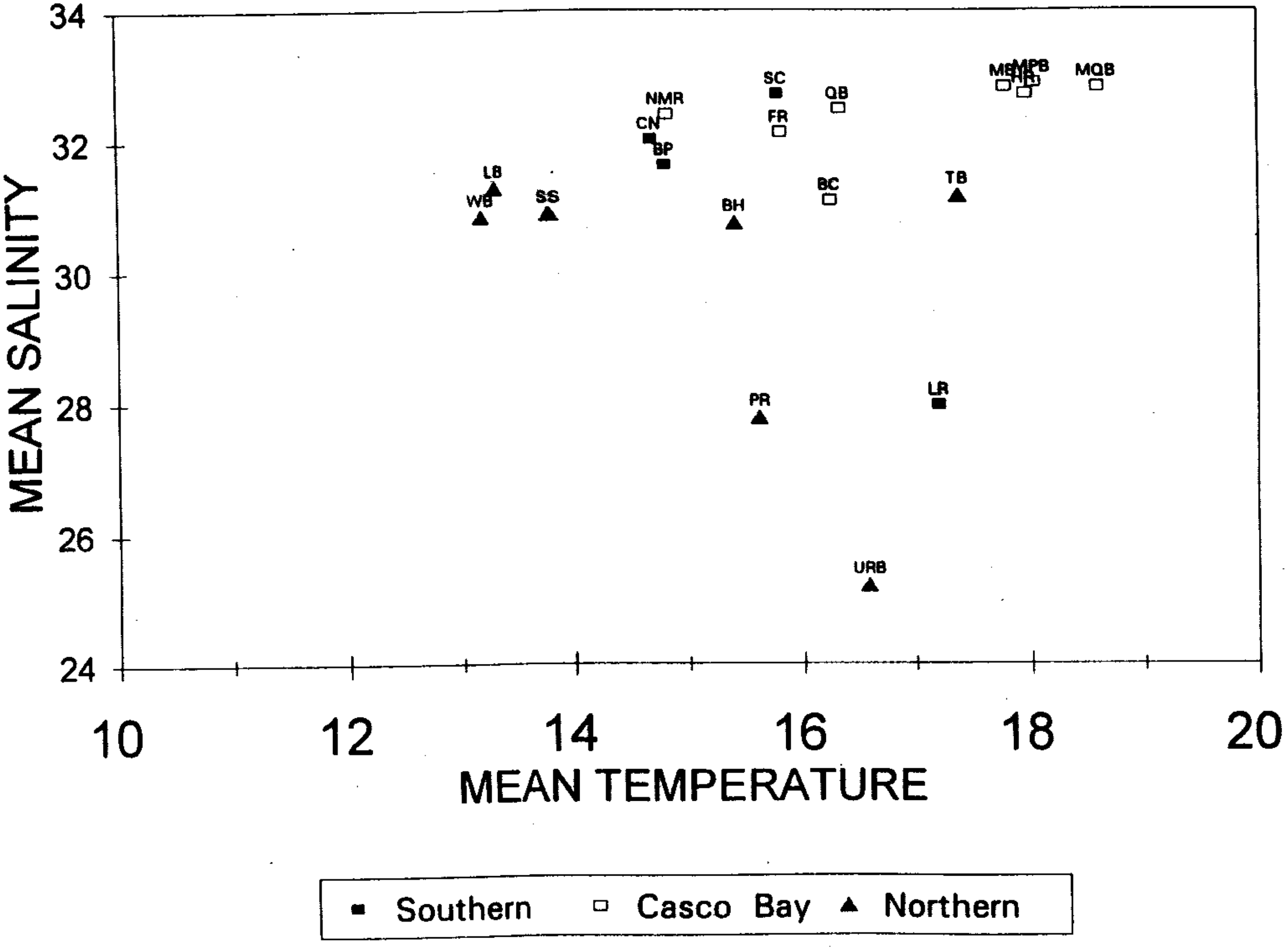


Figure 11. Mean salinity versus mean temperature for each system (all data).

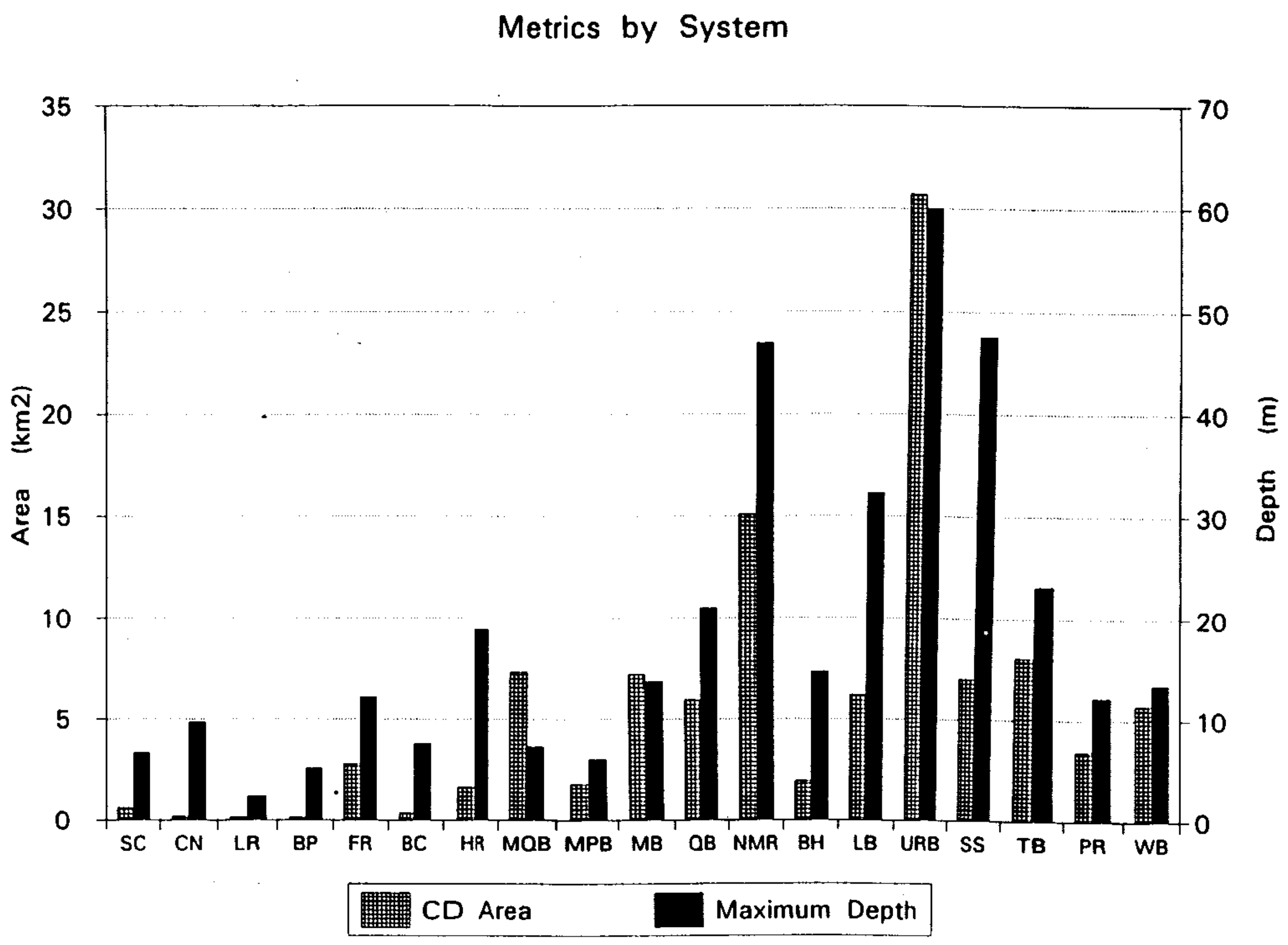


Figure 12. Geomorphic and hydrologic metrics for the selected estuaries and embayments.

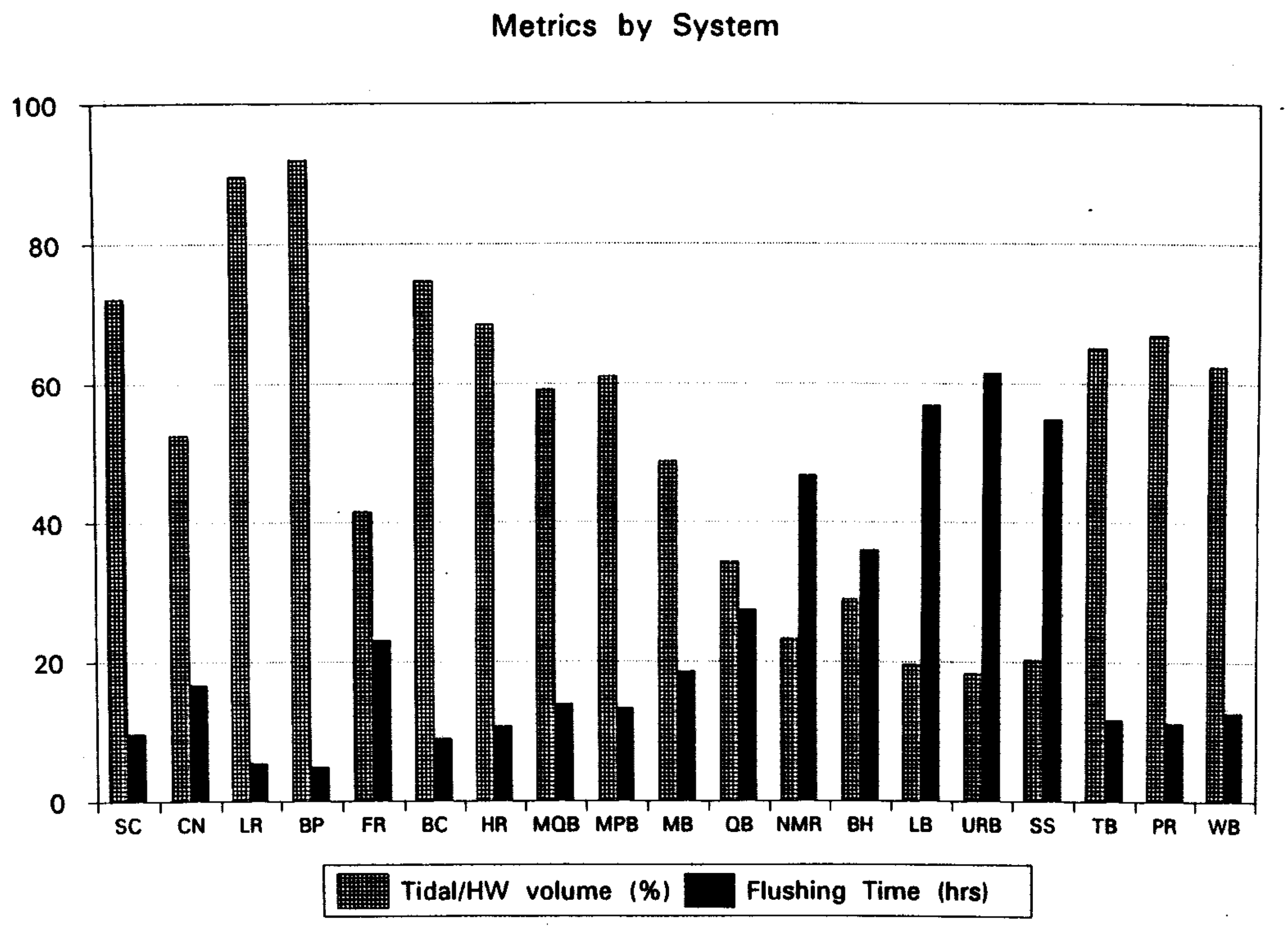


Figure 13. Geomorphic and hydrologic metrics for the selected estuaries and embayments.

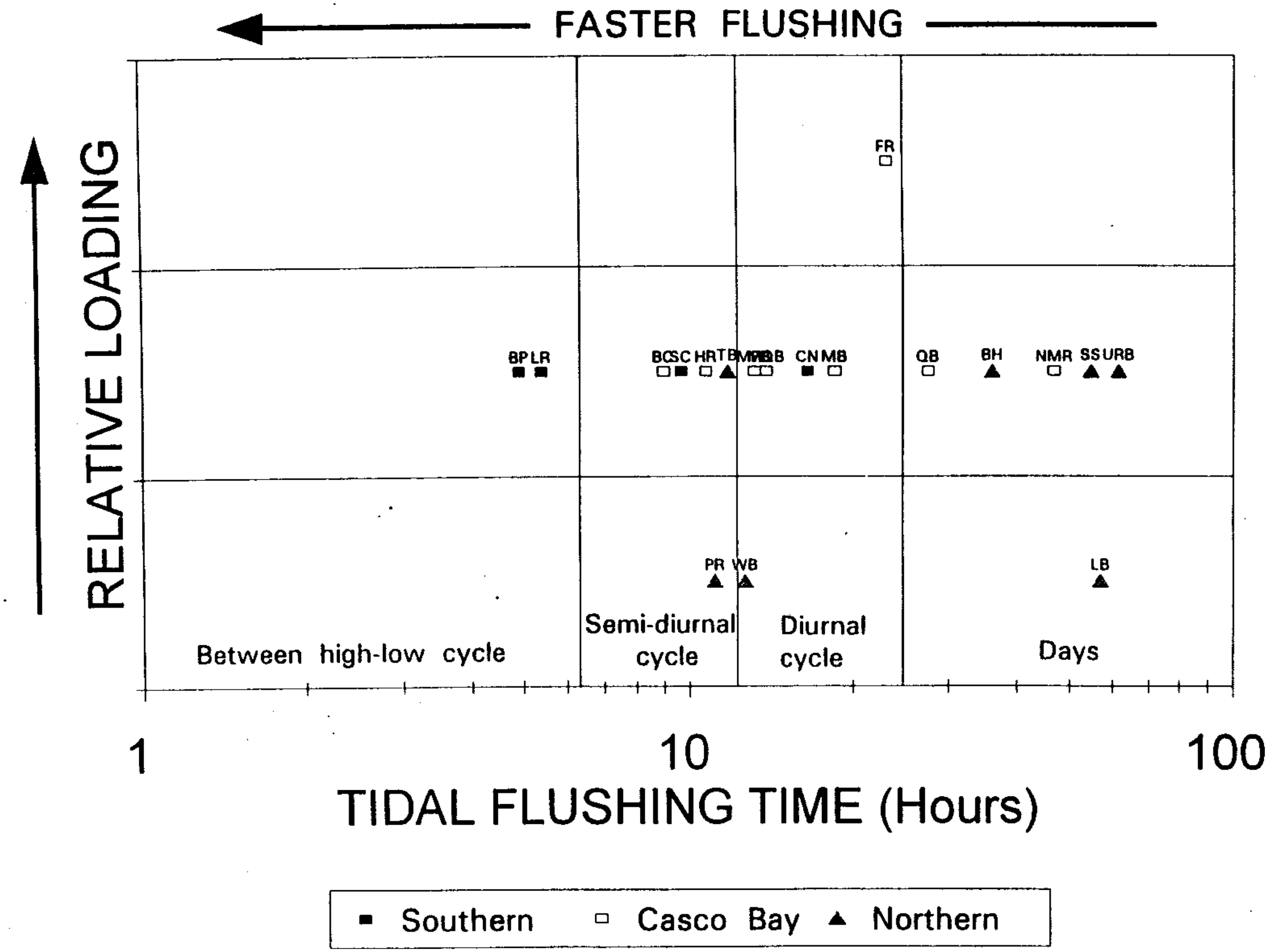


Figure 14. Comparison of system attributes: relative loading vs. tidal flushing time..

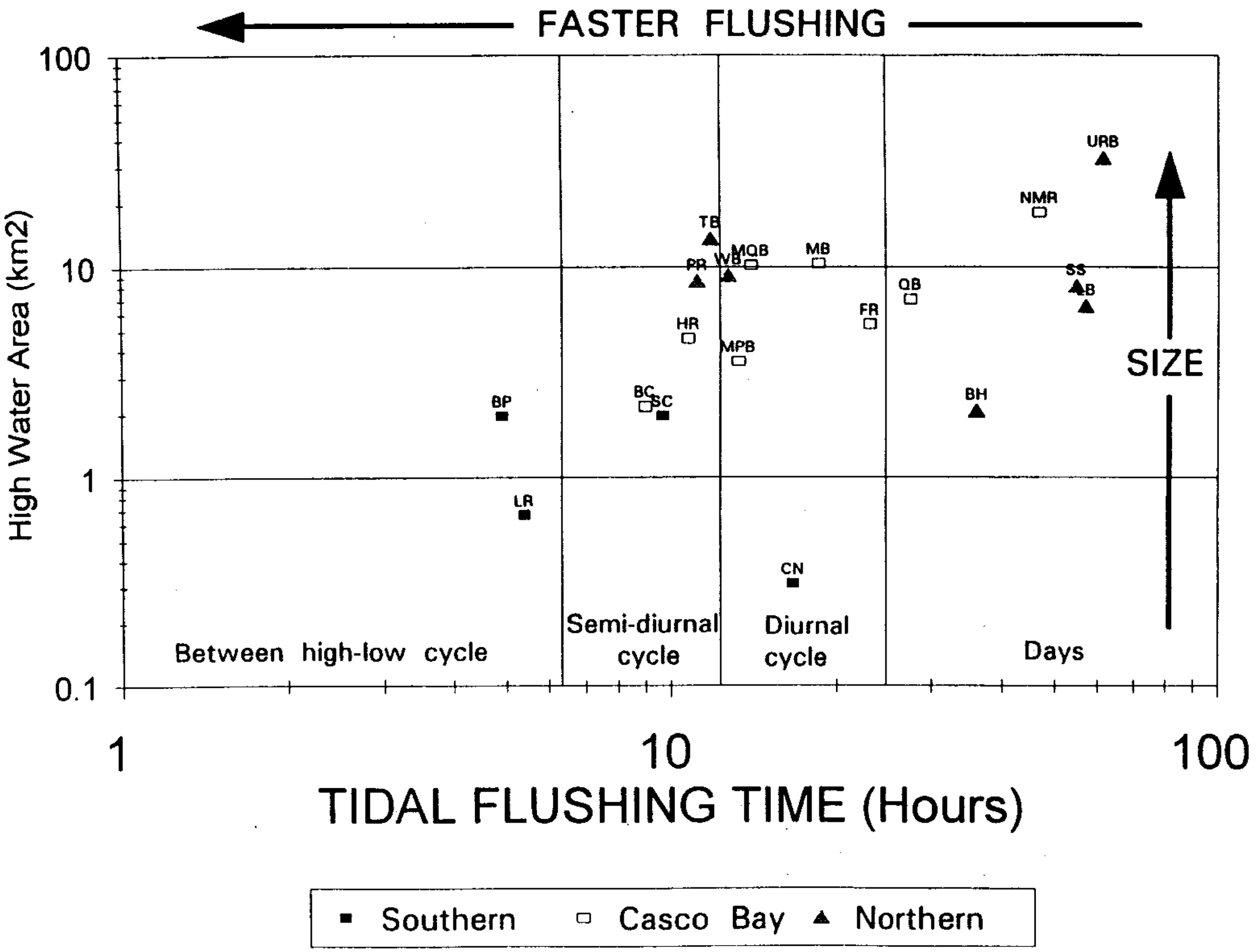


Figure 15. Comparison of system attributes: high water area vs. tidal flushing time.

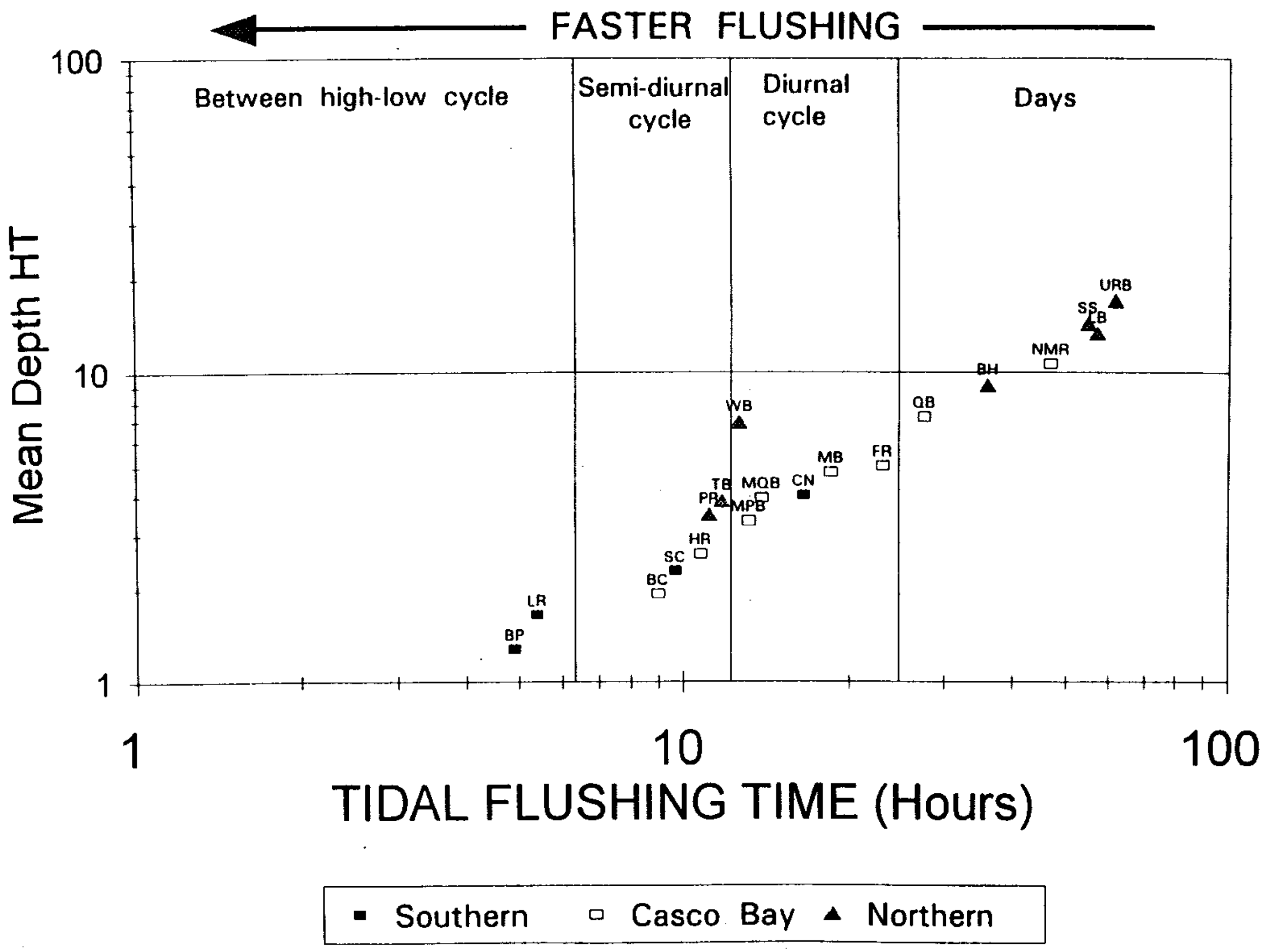


Figure 16. Comparison of system attributes: mean depth at high tide vs. tidal flushing time.

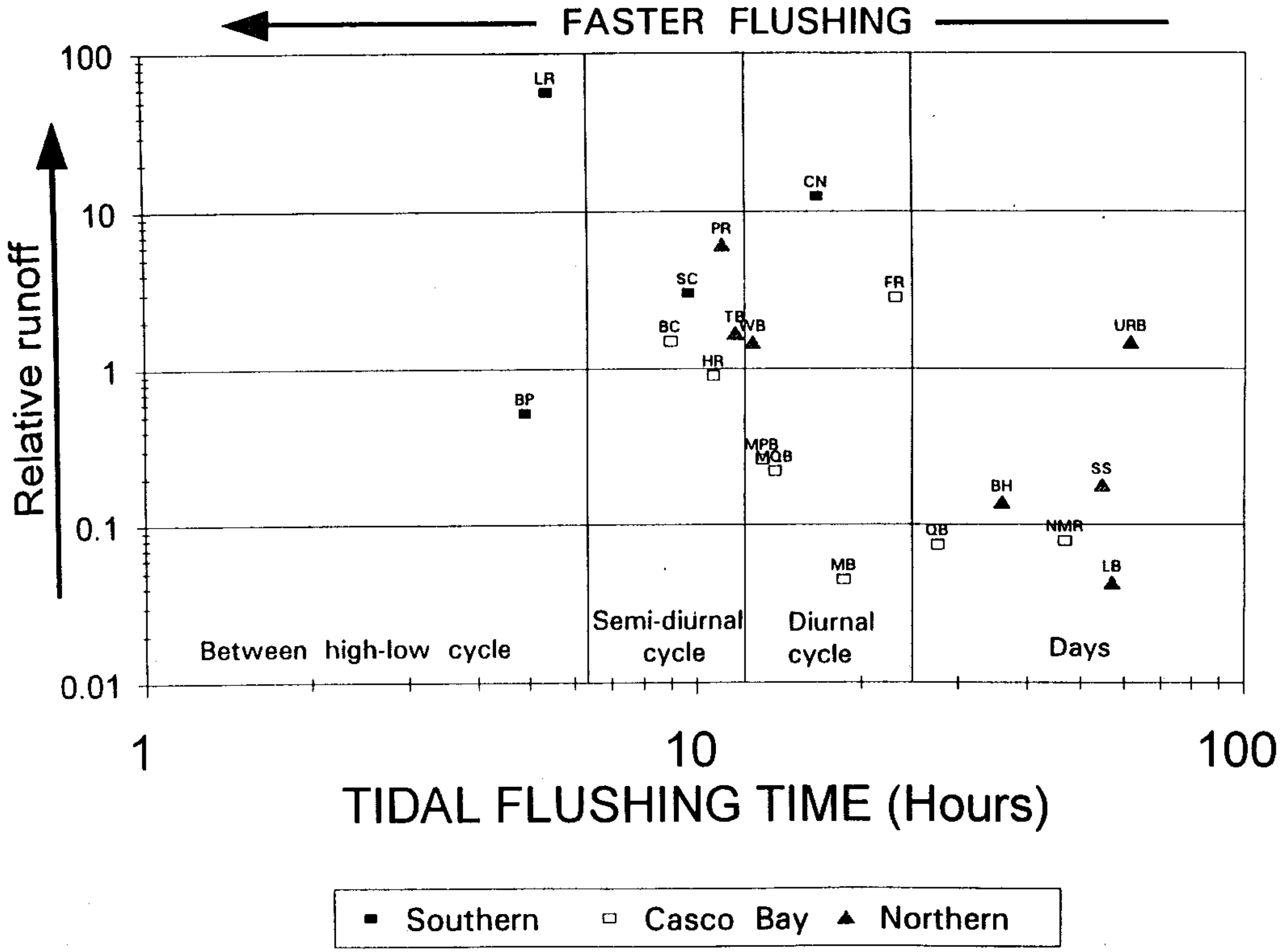


Figure 17. Comparison of system attributes: relative runoff vs. tidal flushing time.

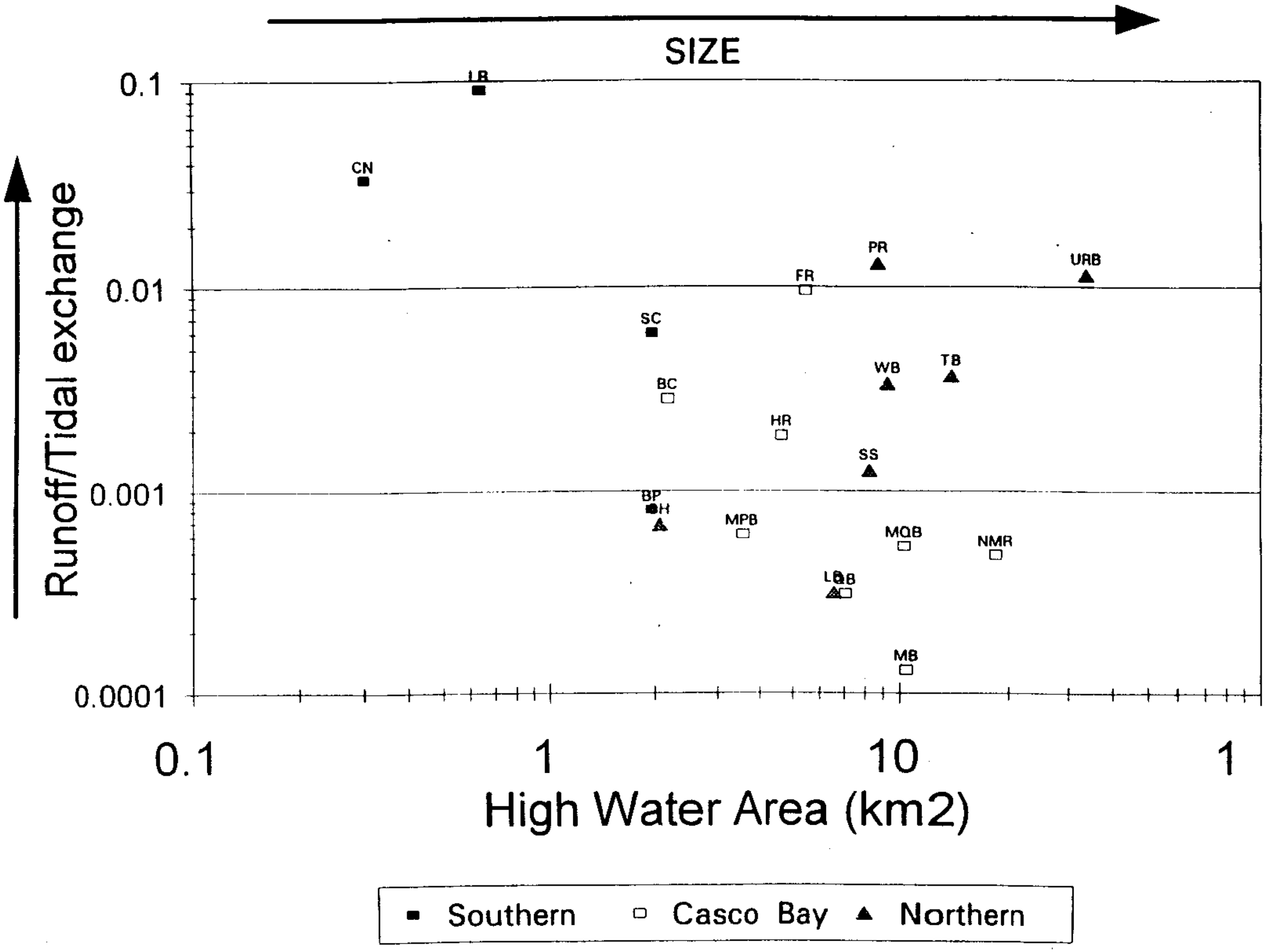


Figure 18. Comparison of system attributes: runoff/tidal exchange vs. high water area.

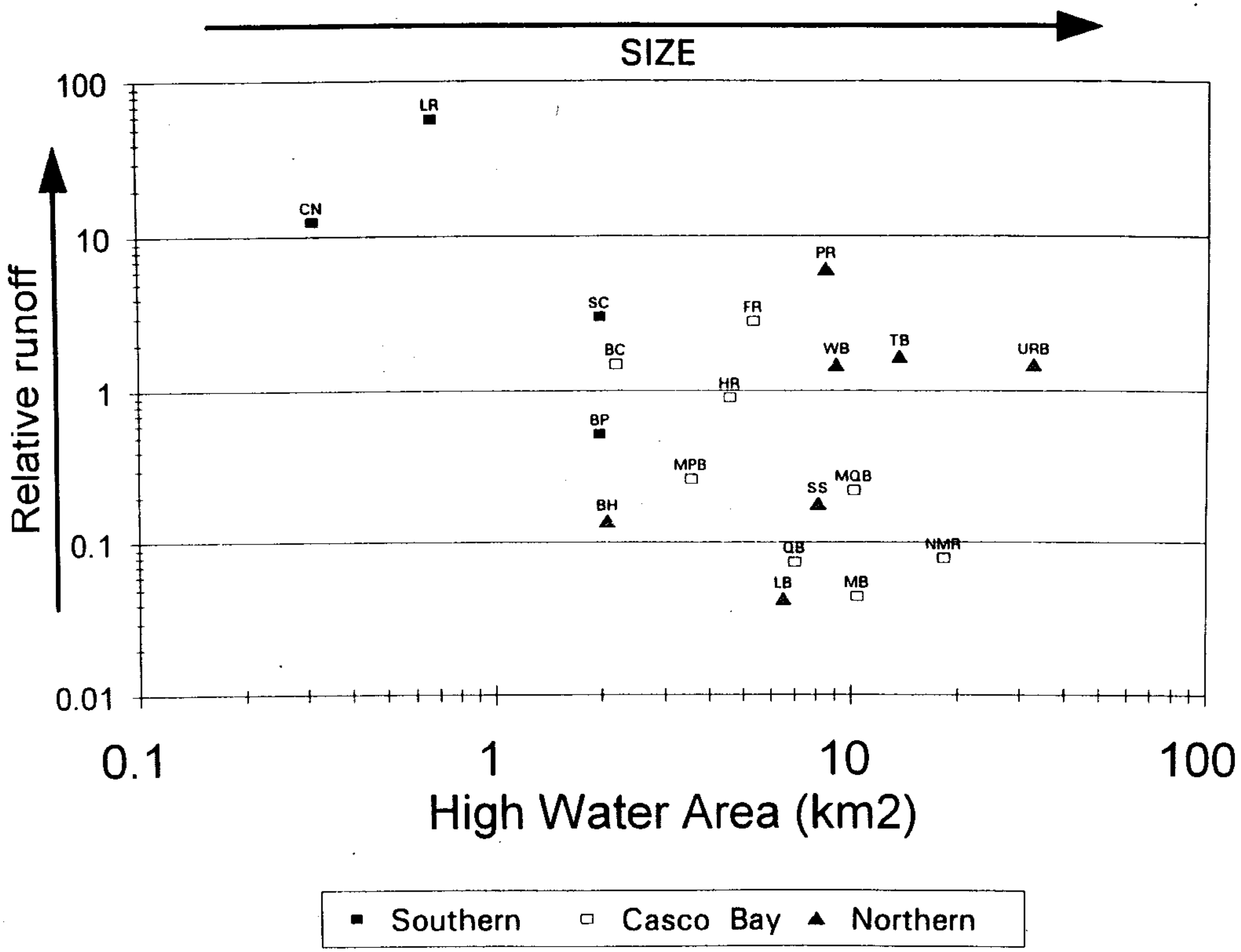


Figure 19. Comparison of system attributes: relative runoff vs. high water area.

ADDENDUM

TO

FINAL REPORT

ON

DISSOLVED OXYGEN LEVELS

IN SELECT MAINE

ESTUARIES AND EMBAYMENTS

--

SUMMER 1995

Detailed Analysis of the Influence of Stratification

on Dissolved Oxygen

March 15, 1996

INTRODUCTION

This addendum provides further analysis of the field data set for 19 coastal ecosystems of Maine from New Hampshire to Canada (Figure 1) that was collected from July to September 1995. The focus of this follow-up analysis is the potential influence of water column stratification on levels of dissolved oxygen (DO). The interested reader may refer to Turner *et al.* (1987), Breitburg (1990), and Stanley and Nixon (1992) for studies in other US coastal areas that have explicitly examined patterns of hypoxia, physical factors, and stratification.

This task extends the initial exploratory analyses of the data (Kelly and Libby, 1996), where patterns of DO in time and space and across ecosystems were described and relationships among DO and other factors were identified. The overall goal of the data collection and analyses efforts is to define a relationship(s) that could serve as an index to broadly classify susceptible areas and aid planning for source control of nutrients to all coastal water bodies in Maine.

METHODS

For each sampling event for which appropriate data were available (n=3611), seawater density (as Sigma-T) was calculated following standard conventions (Fofonoff and Millard 1983). A copy of the program to make these calculations is attached as an appendix.

To provide a stratification index, we calculated the density difference between the bottommost and surfacemost reading of each vertical profile. Precedents exist for using this index (cf. Turner *et al.*, 1987; Stanley and Nixon, 1992) even though it simplifies the overall shape of individual density profiles. We refer to the index as Delta Density or Delta Sigma-T. A single value was calculated for each profile. In the data file, the value was included as an entry for each sampling event of the entire profile; this provided more flexibility to compare measurements made anywhere within the profile to the single index for the station's profile.

In performing the calculations for Delta Sigma-T, we discovered a few errors in the previous coding of sampling events with respect to whether they were surface or intermediate depths. Less than a dozen events were recoded with respect to depth (see appendix). In examining the data, a few points were identified as isolated points that were not part of a full profile; these were deleted from the file and are also indicated in the appendix. The revised data file (n= 3606 events) used for analyses reported here is provided on an floppy disk with this addendum. Summary statistics for each of the 19 systems, including the new variables Sigma-T (density) and Delta Sigma-T, are provided in the appendix.

RESULTS AND DISCUSSION

Figure A-1a shows the frequency distribution for Sigma-T (n=3602; this excludes 4 points where a negative density was calculated). Figure A-1b indicates that low density values are a function of low salinity.

Figure A-2 shows a frequency distribution for the stratification index as calculated from all (n=470) profiles in 1995. We excluded one index value where a Sigma-T value was <0. A small percentage of the values for Delta Density were <0. We chose not to exclude negative Delta Sigma-T values from the analysis; however, their exclusion would not change the fundamental results. More than 85% of the values were <2.25. Figure A-2 partitions the data into low tide and high tide sampling. It can be seen from the figure and was confirmed by a Kruskal-Wallis test (non-parametric) that Delta Sigma-T near low tide (mean 1.2) was not significantly different from high tide (mean 0.9) (CHISQ= 2.4, df=1, Prob>F=0.12).

The mean value and distribution of Delta Sigma-T values for each system are displayed in Figure A-3 (a box and whisker plot, see Kelly and Libby 1996). The primary systems with negative Delta Sigma-T values were Little River and New Meadows River. Systems with higher mean values (near 3) were Little River and Union River Bay. Back Cove and Linekin Bay had values near 2, but in the case of Linekin Bay the mean was highly skewed by two high outliers. Most systems had mean values from 0 to 1 and most individual values below 2. In general, the data suggest the majority of these systems are not highly stratified.

Overall stratification pattern with salinity and DO

Using all station profiles, Delta Density was plotted relative to the surface and bottom salinity (Figure A-4). There was no discernible relation with bottom salinity; in contrast, there was a (weak) negative linear relationship with surface salinity. The patterns suggest that stronger stratification generally related to the presence of fresher water at or near the surface in some systems.

Overall, there was not striking pattern of bottom-water DO concentration as a function of the strength of stratification (Figure A-5). Many of the DO concentrations at or below 6 mg L^{-1} were associated with higher values of Delta Sigma-T, but the lowest DO concentrations were found at a Delta Sigma-T of about 0.

Regression modeling: DO and environment

Parallel to Kelly and Libby (1996), we conducted stepwise multiple regression that examined DO variability as a function of time and physical variables, now including Delta Sigma-T as one of the independent variable choices.

Using all data (n=3602), and either DO concentration or %saturation as the dependent variable, significant (95% level) models were obtained that were very similar to the previous analysis. Delta Sigma-T was added to the model, but the partial correlation coefficient was very low (≥ 0.001). As before, day of the year (DOY) had the highest partial correlation coefficient (0.21). An example full model was:

$$\begin{aligned}&\text{DO (\%sat)} = \\ &54.5 + 10.4\,(\text{T},{}^\circ\text{C}) - 0.28\,(\text{T},{}^\circ\text{C})^2 + 0.99\,(\text{S, ppt}) + 0.03\,(\text{Z, ft}) \\ &- 0.338\,(\text{DOY}) + 2.0\,(\text{Time relative to low tide}) - 0.29\,(\text{Time relative to low tide})^2 \\ &-0.27\,(\text{Delta Sigma-T}),\ \text{with } r^2 = 0.34,\ df=3591,\ Pr > F = 0.0001.\end{aligned}$$

Using only bottom-water DO data, Delta Sigma-T was also included in the multiple regression. The resultant full model was:

$$\text{DO (mg L}^{-1}) = 6.59 + 0.013\,(Z, \text{ft}) - 0.021\,(\text{DOY}) - 0.091\,(\text{Delta Sigma-T}) + 0.046\,(S, \text{ppt}) + 0.647\,(T, ^\circ\text{C}) - 0.22\,(T, ^\circ\text{C})^2$$

with $r^2 = 0.32$, df =469, $Pr > F = 0.0001$.

Results did not differ substantially from the previous analyses without Delta Sigma-T nor do they indicate a strong contribution of stratification to explaining the variability of DO in the overall data set. The regressions, like the previous ones, suggest that physical and temporal parameters can explain only about ⅓ of the DO variability, leaving the majority of the DO variability to be explained by other factors, including differences in morphometrics, flushing, and loading among systems.

Observations on patterns across and within systems

The lowest DO concentrations were measured in Spruce Creek, as shown in Figures A-6 and A-7. These plots employ two DO metrics used in Kelly and Libby (1996) as the dependent variable. The metric, low 5% of the DO values (Figure A-6), selected data independent of time, depth, or month of sampling. The metric, Low Tide September, Bottom Water, selected the bottommost value of every station profiled at that month within each system. For both DO metrics, lower DO values and higher Delta Sigma-T values derived from Little River. Omitting data for Spruce Creek, the following significant linear regressions were obtained:

$$\text{Low 5\% DO (mg L}^{-1}) = 7.21 - 0.175\,(\text{Delta Sigma-T}),$$

($r^2 = 0.26$, df= 150, $Pr>F = 0.0001$) (see Figure A-6)

and

$$\text{Low Tide Sept Bottom DO (mg L}^{-1}) = 7.63 - 0.132\,(\text{Delta Sigma-T}),$$

($r^2 = 0.37$, df= 66, $Pr>F = 0.0001$) (see Figure A-7).

The regressions explain about ¼ to ⅓ of the variance in the data and the patterns thus do suggest some tendency for lower DO to be associated with stronger stratification. This tendency is expressed *across* systems (e.g. Figure A-6). To a degree it is also expressed *within* systems (i.e., across stations) in September, the sampling with characteristically lowest DO concentrations (see Kelly and Libby 1996). However, note that there was not a large range in bottom DO across stations in most systems in September and both patterns tend to be driven by the low values in Little River.

We further examined patterns across stations within selected systems to assess if the lowest DO was consistently associated with higher *local* stratification. We concentrated on data from August and September, when DO concentrations were reaching seasonal lows. Examples are shown for types of systems in Figures A-8 and A-9, where all data are low tide profiles..

Type 1: High stratification (Figure A-8). This type is represented by Little River and Union River Bay, the former with very low DO and the latter with medium DO (Kelly and Libby 1996).

In Little River, while the degree of stratification increased up-estuary (from station 1 to 4), DO concentrations were not very different across stations and DO was rather uniformly low throughout the water column (Figure A-8).

Lowest DO concentrations in Union River Bay were in the bottom water (~70 ft) at station 2, which had very slight stratification compared to a number of shallow up-estuary stations where surface densities were below 10 (Figure A-8). At shallow stations in Union River Bay, there was a strong tendency for bottom waters to have much lower DO concentrations than surface waters.

Type 2: Low stratification (Figure A-9). This type is represented by Fore River and Spruce Creek, the former with high DO and the latter with low DO (Kelly and Libby 1996).

In Fore River, there was very slight stratification, even with a relatively deep water column. DO concentrations did not differ over depth or among stations.

In Spruce Creek, there was little vertical stratification at any of the four stations. The station profiles for DO were uniform with depth, but there was a tendency for DO concentrations to decrease up-estuary, from station 1 to station 4. The low DO in September (below 5 mg L^{-1}), noted previously in Spruce Creek, occurred near the surface, not in bottom water, and was not related to strong stratification. That data may be questionable; if not, there is suggested a strong source of oxygen depletion in the local area.

From these few examples, it is seen that a variety of general and local DO patterns exist and the lower DO concentrations, within or across systems, are not consistently correlated to more intense stratification. Having said that, there are *particular* cases where local stratification and lower DO occur concomitantly.

Inclusion of stratification in morphometrics and DO cross-system analyses

We determined the mean and maximum Delta Sigma-T during August and September for each of the 19 systems (see appendix). We then used this to compare to DO levels and to other morphometrics previously examined.

With respect to DO, we repeated the Multiple Regression Analyses (e.g., p. 12 of Kelly and Libby 1996) which regressed environmental and morphometric variables against the selected DO metrics, including also mean and maximum Delta Sigma-T values for each system. In a series of regressions with the different metrics, only in one instance was a stratification variable included in a regression model, and it was not one of the best models given in Kelly and Libby. The result was therefore that the inclusion of a stratification variable did not change the regression modeling results that were previously reported.

In order to place some perspective on stratification in the context of the different systems, we produced Figures A-10 and A-11, which compliment those in Kelly and Libby and further distinguish differences among systems. There was a weak relationship between stratification and salinity (cf. Figure A-4) and depth (omitting Little River), but no real relation between stratification and relative runoff, or the runoff/tidal exchange ratio. The system that stands out as fairly unique on many of these plots is Little River, the system with demonstrably and statistically lower DO than the others (see Kelly and Libby 1996). Nowhere are Little River's unique physical and dynamic qualities more evident than in Figure A-12, which places all the systems on a stratification/flushing diagram.

SUMMARY

What have we learned relative to stratification and vulnerability to low DO? We can summarize the data in reference to Figure A-12. Little River is small, flushed quickly, but it's rather strongly stratified due to a relatively high freshwater runoff. Interestingly, Union River Bay and Linekin Bay are at the other end of the flushing spectrum and are also relatively strongly stratified. These two systems are not as small as Little River and each has relatively high DO. Everything else being equal, one would think the slow flushing, more highly stratified systems (e.g., Union River Bay and Linekin Bay) would have more vulnerability to low DO. It is counterintuitive to find that, in contrast, the rapidly flushed system — Little River — has low DO. As described previously, Little River stands out for another attribute, it has a much higher freshwater input per unit area than other systems (relative runoff, i.e., freshwater loading). Unfortunately, we do not yet know if its organic loading is also high compared to other systems. Its relatively high runoff, which may carry a substantial oxygen demand, additionally appears to produce notable vertical stratification, and this may be part of the key to its generally lower DO.

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Kelly, J.R. and P. S. Libby. 1996. Dissolved Oxygen in Maine Estuaries and Embayments. Final Report to Wells National Estuarine Research Reserve, 342 Laudholm Rd., Wells, ME 04090. February. 46 pp.

Fofonoff, N.P. and R. C. Millard, Jr. 1983. Algorithms for computation of fundamental properties of seawater. *UNESCO Technical Papers in Mar. Sci.* 44.

Stanley, D.W. and S. W. Nixon. 1992. Stratification and bottom-water hypoxia in the Pamlico River Estuary. *Estuaries* 15:270-281.

Turner, R., W. Schroeder, and W. Wiseman, Jr. 1987. The role of stratification in the deoxygenation of Mobile Bay and adjacent shelf bottom waters. *Estuaries* 10(1): 13-19.

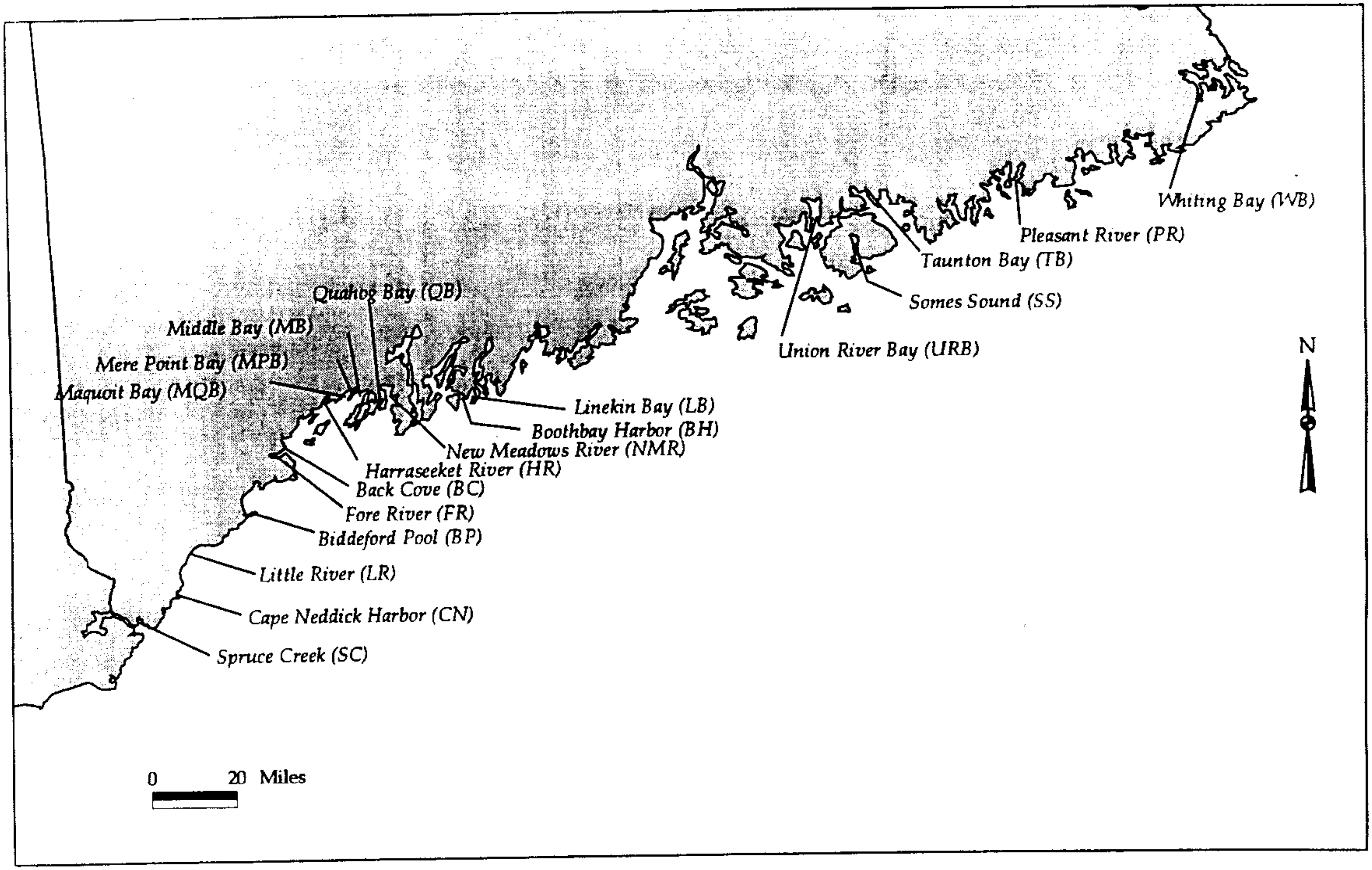


Figure 1. Maine Estuaries and Embayments: Selected Study Areas 1995

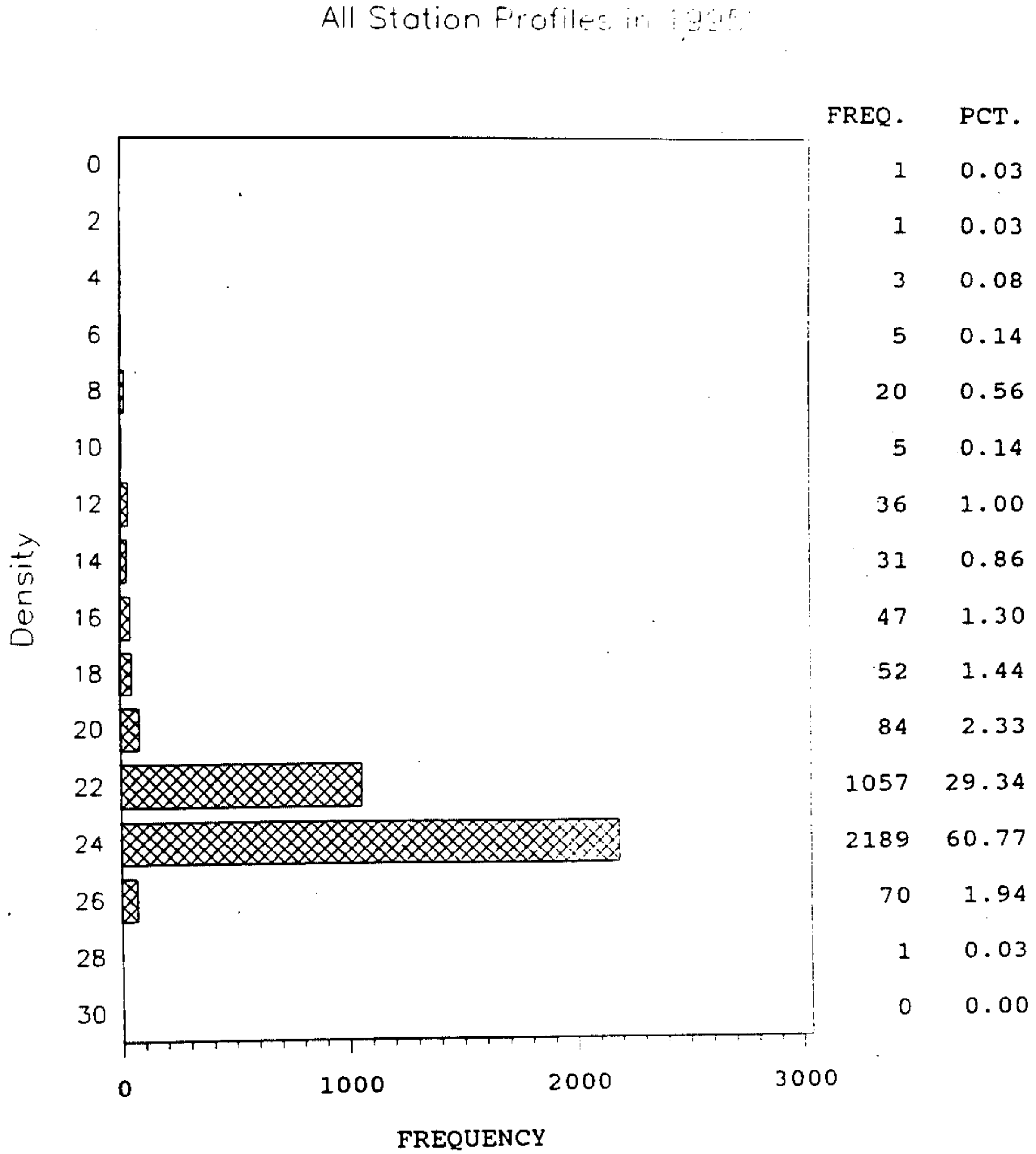


Figure A-1a: Frequency distribution of density (Sigma-T) calculated from 1995 data.

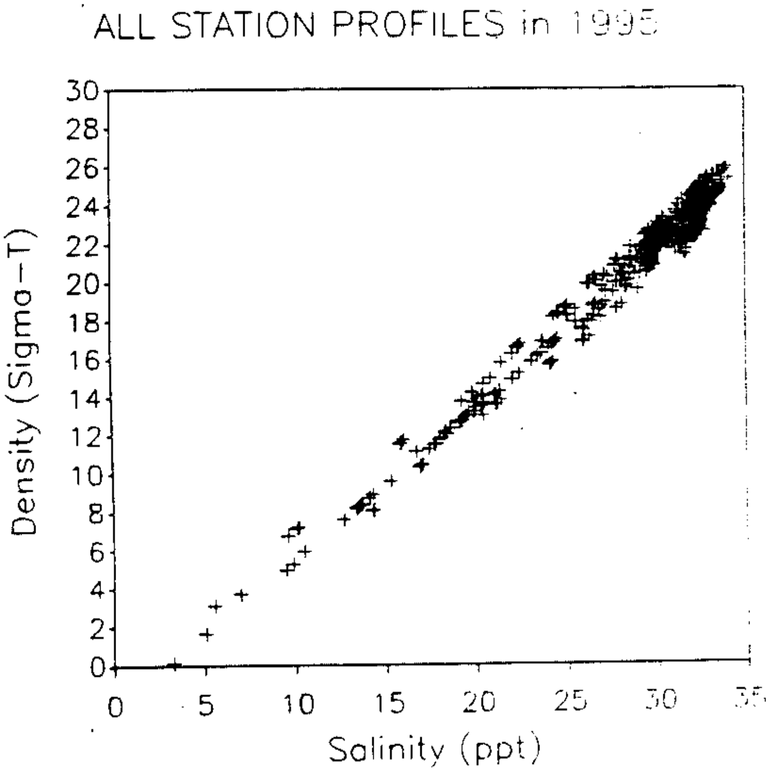
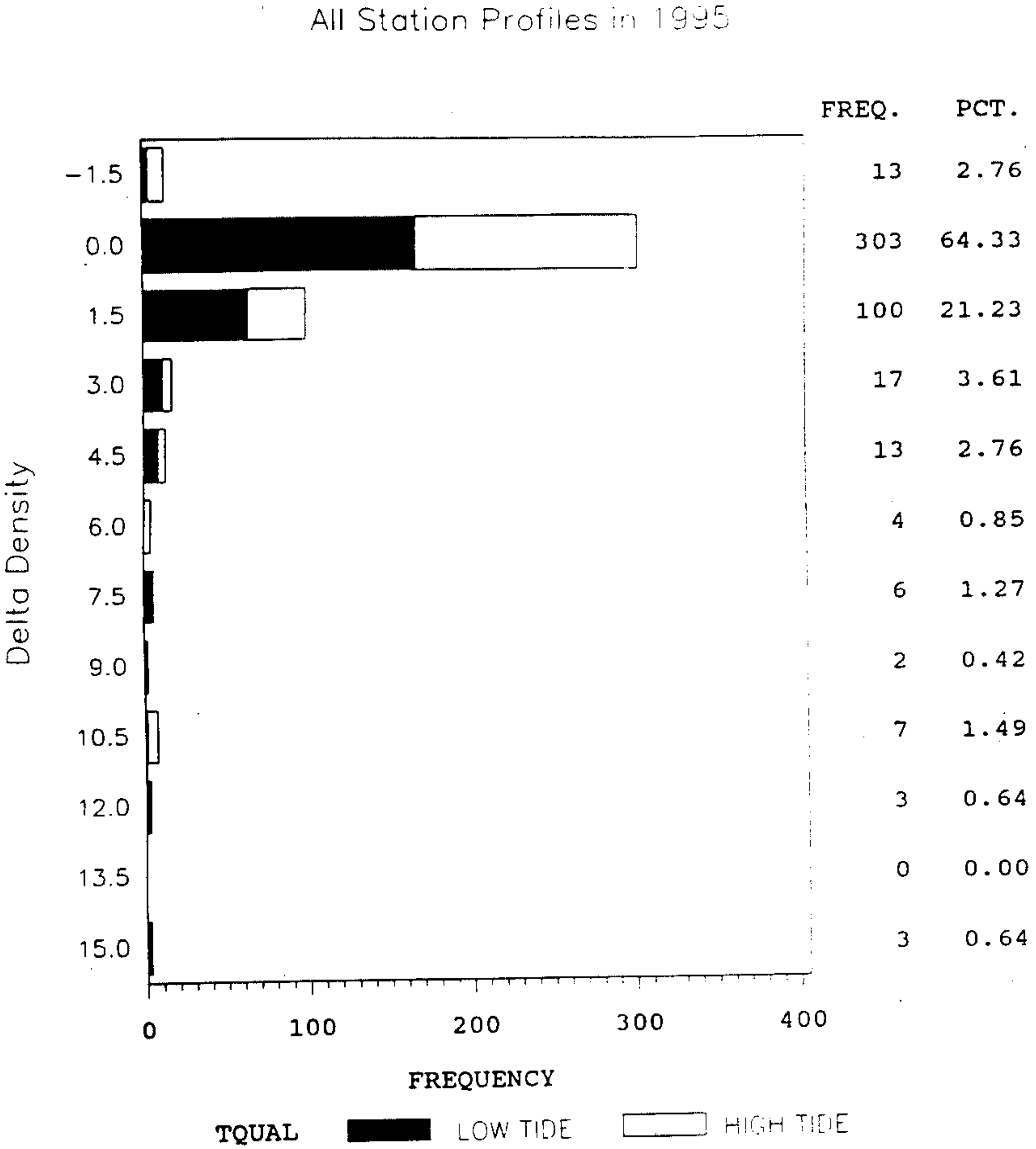


Figure A-1b. Calculated density as a function of measured salinity in 1995.



Delta Density	FREQ.	PCT.
-1.5	13	2.76
0.0	303	64.33
1.5	100	21.23
3.0	17	3.61
4.5	13	2.76
6.0	4	0.85
7.5	6	1.27
9.0	2	0.42
10.5	7	1.49
12.0	3	0.64
13.5	0	0.00
15.0	3	0.64

Figure A-2: **Frequency distribution of Delta Density (defined in text) in 1995. Stacked bars show distribution for sampling near low tide and high tide.**

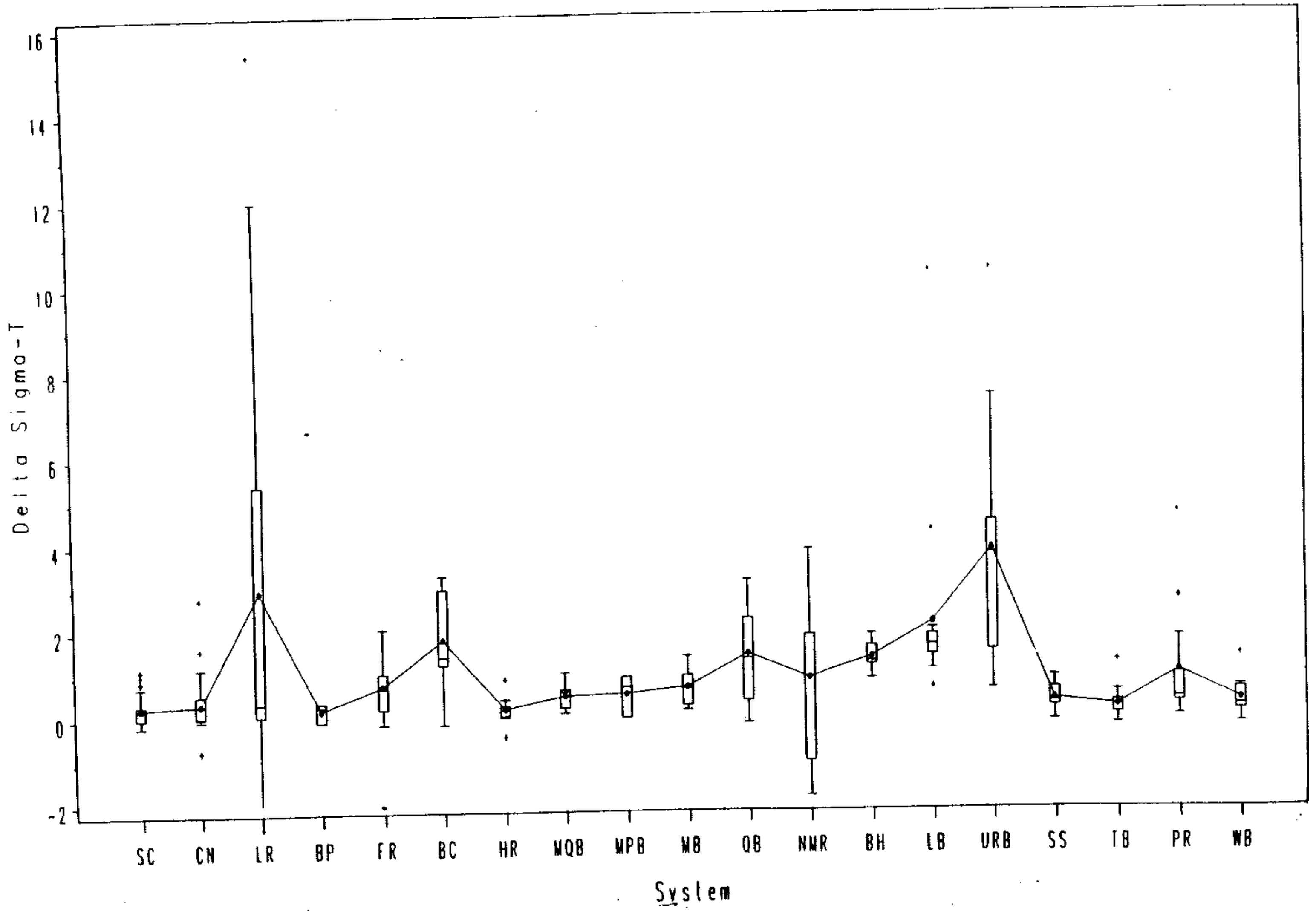


Figure A-3: Box and whisker plot of all Delta Sigma-T in 1995. Mean values are shown by the connected dots. Systems are arranged geographically, south to north, from left to right and system codes are given in Figure 1.

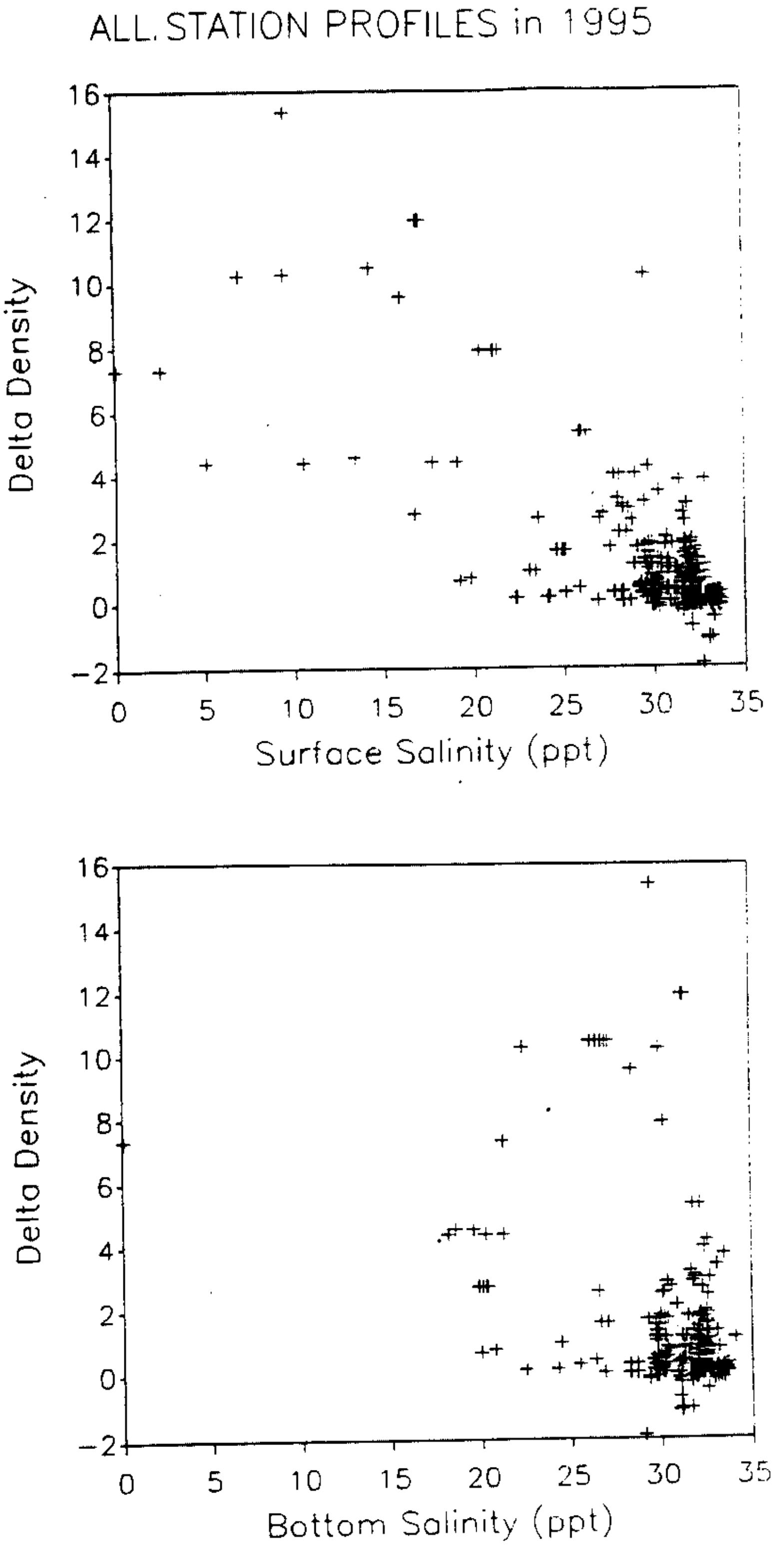


Figure A-4: Delta Density compared to surface and bottom salinity.

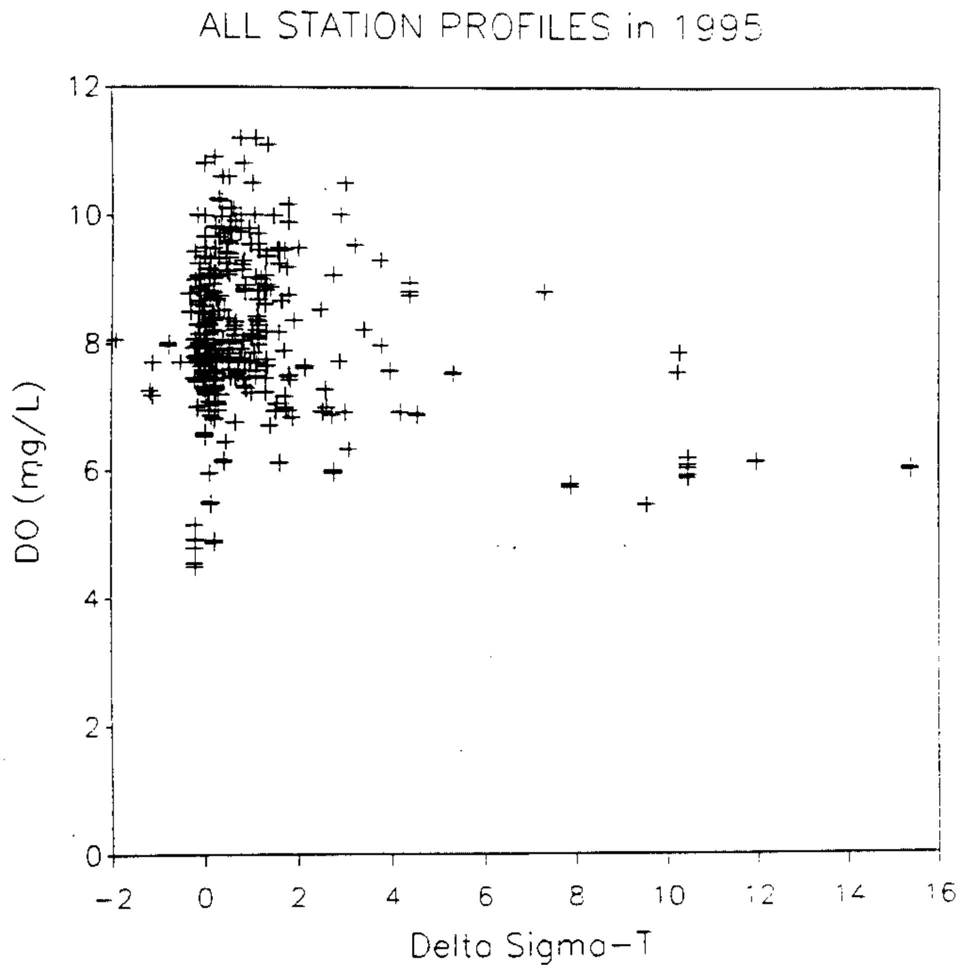


Figure A-5: **Concentration of DO as a function of Delta Density for all data in 1995.**

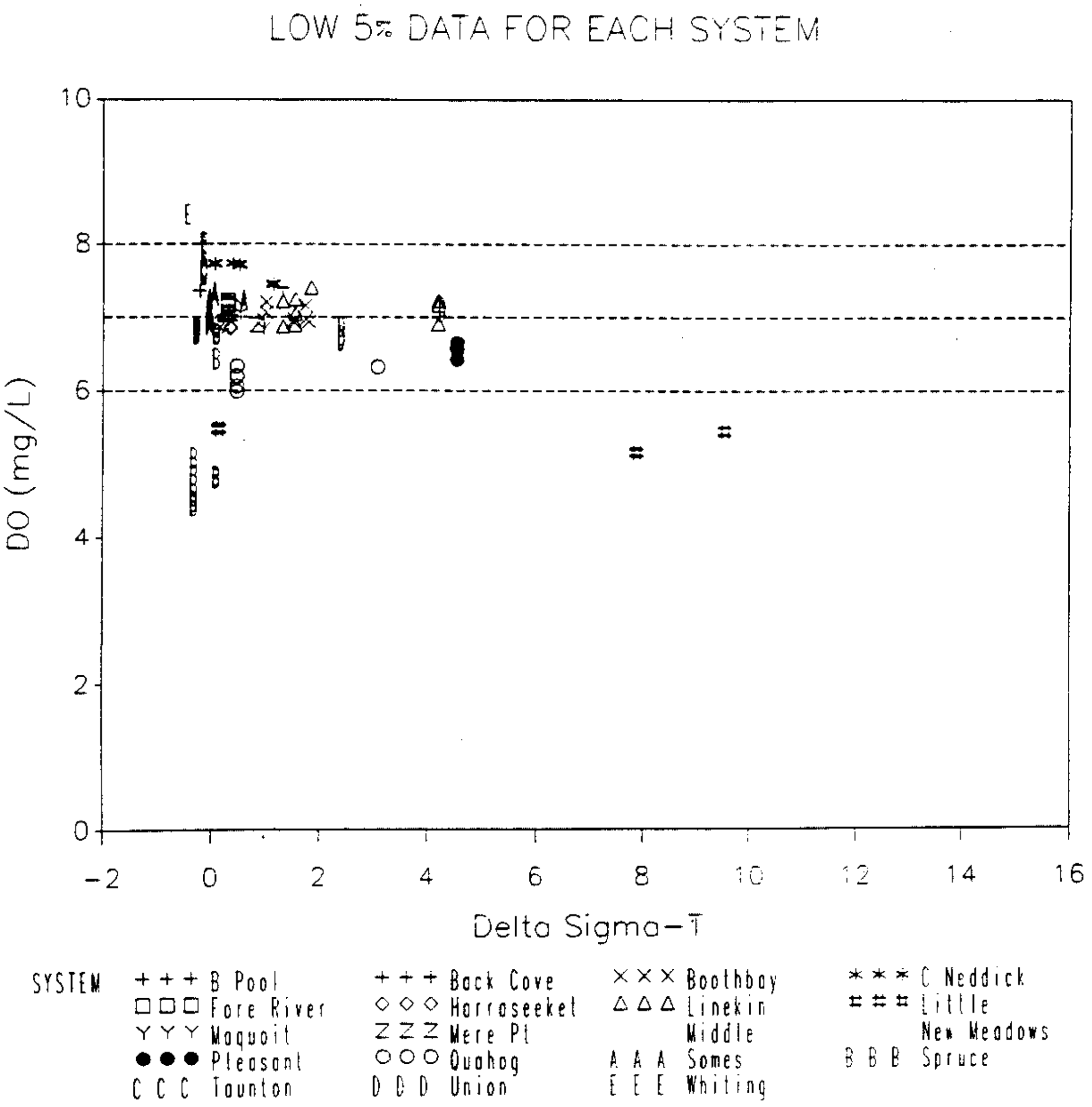


Figure A-6: The lowest 5% of DO concentrations in each system as a function of their associated hydrographic profile's Delta Density.

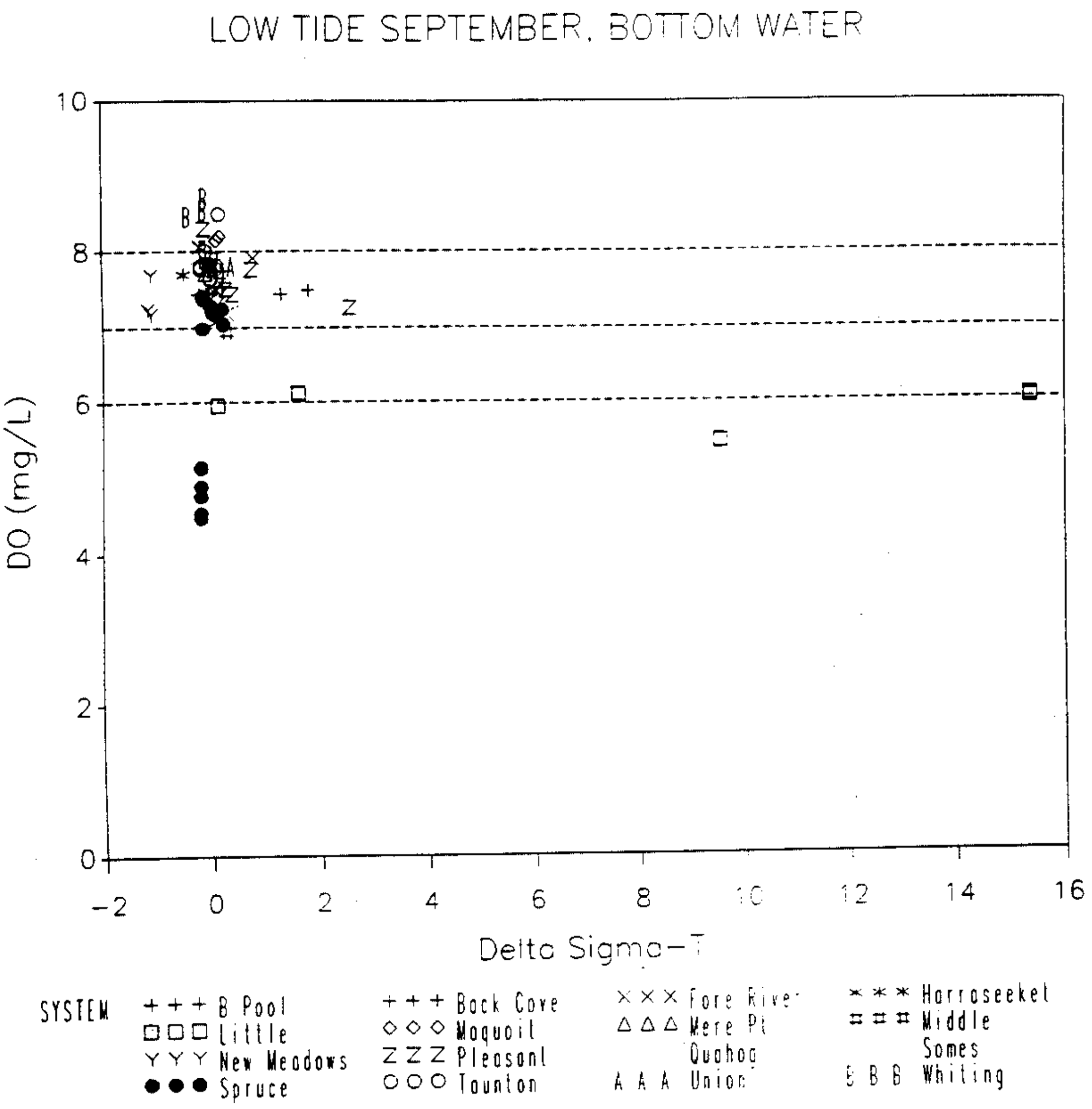


Figure A-7: **Bottom water DO concentrations near low tide in September for all stations in each system as a function of their associated hydrographic profile's Delta Density.**

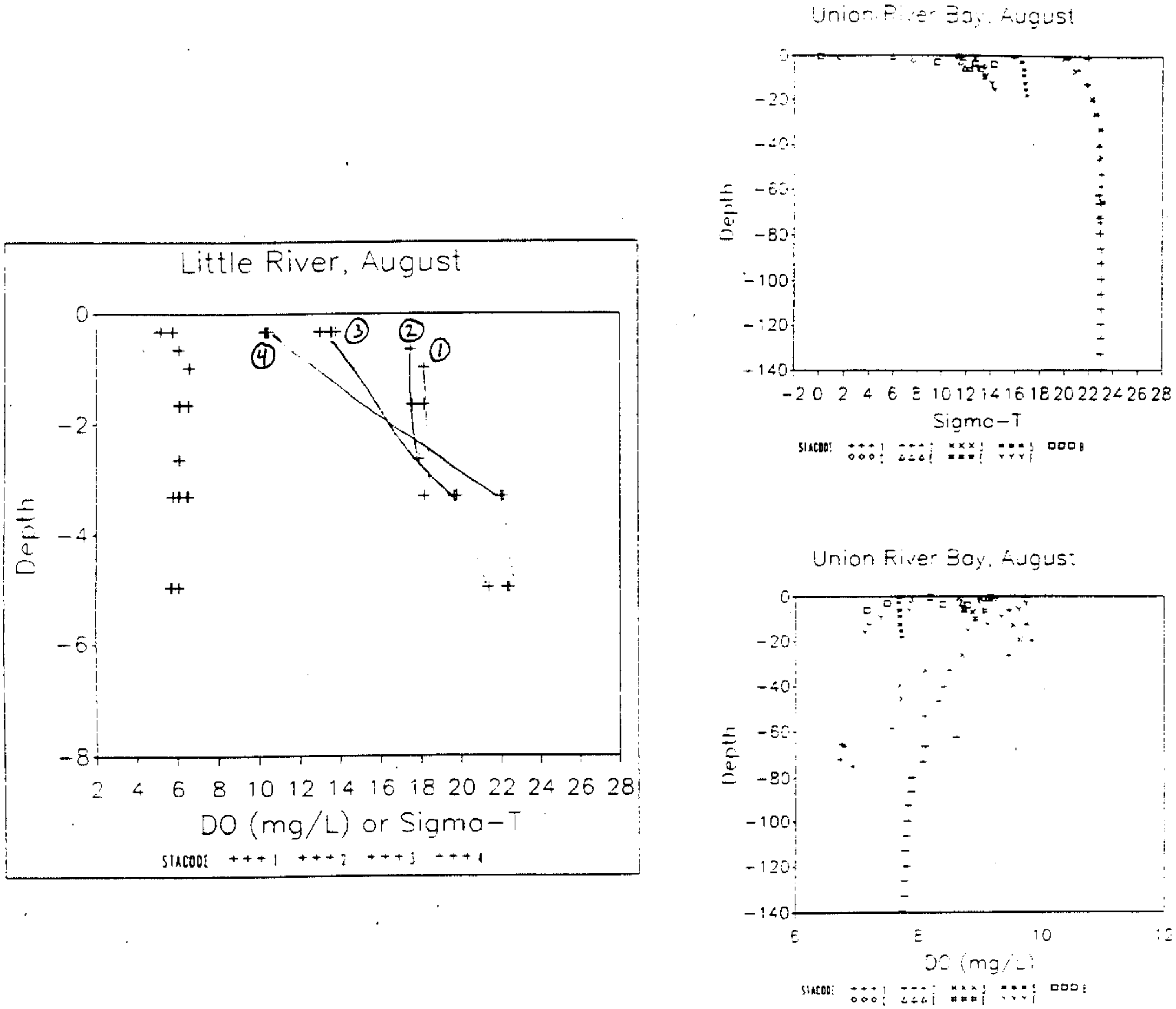


Figure A-8: Station profiles for DO (mg L^{-1}) and density (Sigma-T) for Little River and Union River Bay, two systems with the strongest average vertical stratification. Station 1 is near the mouth of the system and the transect proceeded up the estuary.

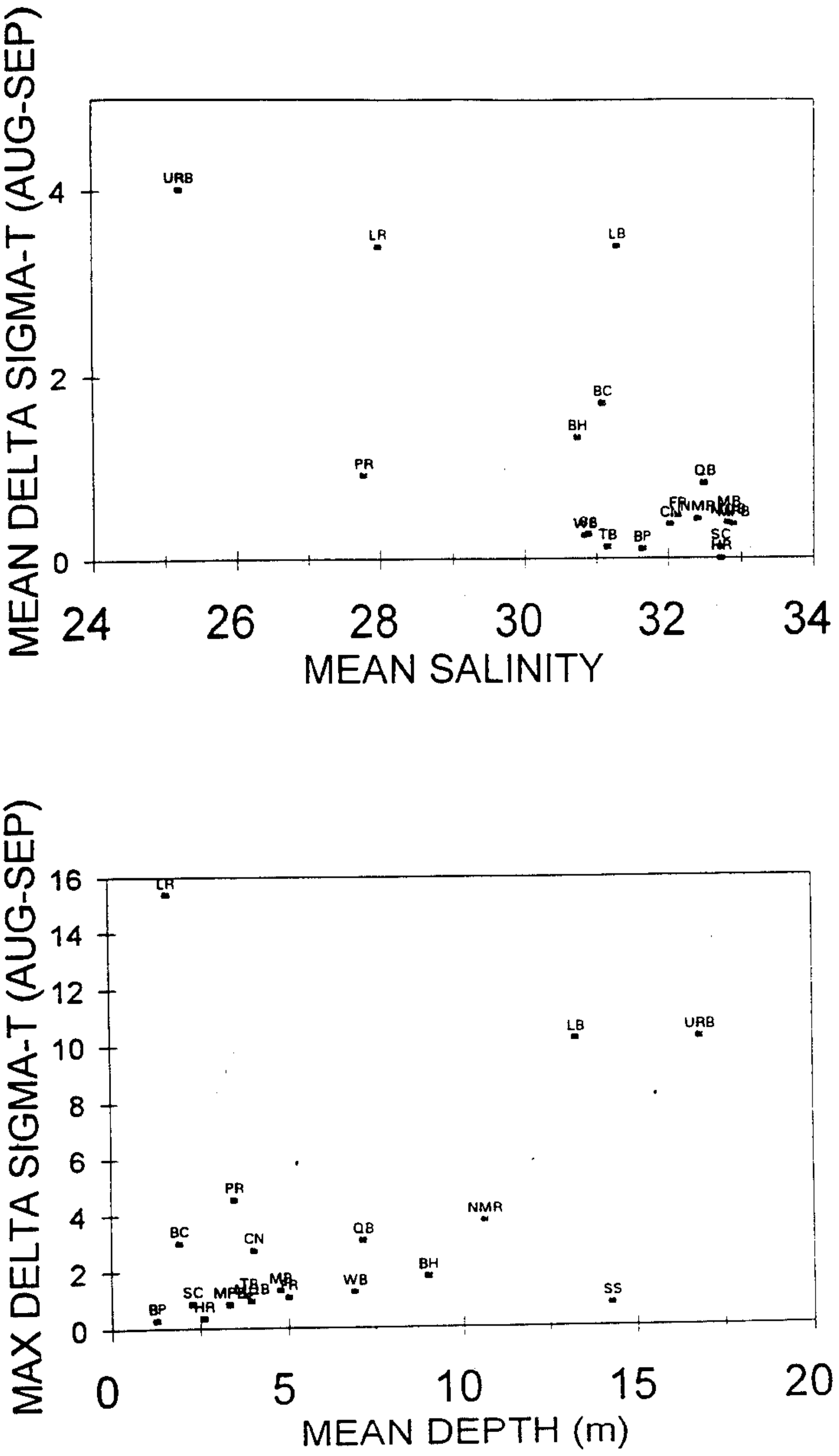


Figure A-10: Stratification indices vs. salinity and depth for all systems.

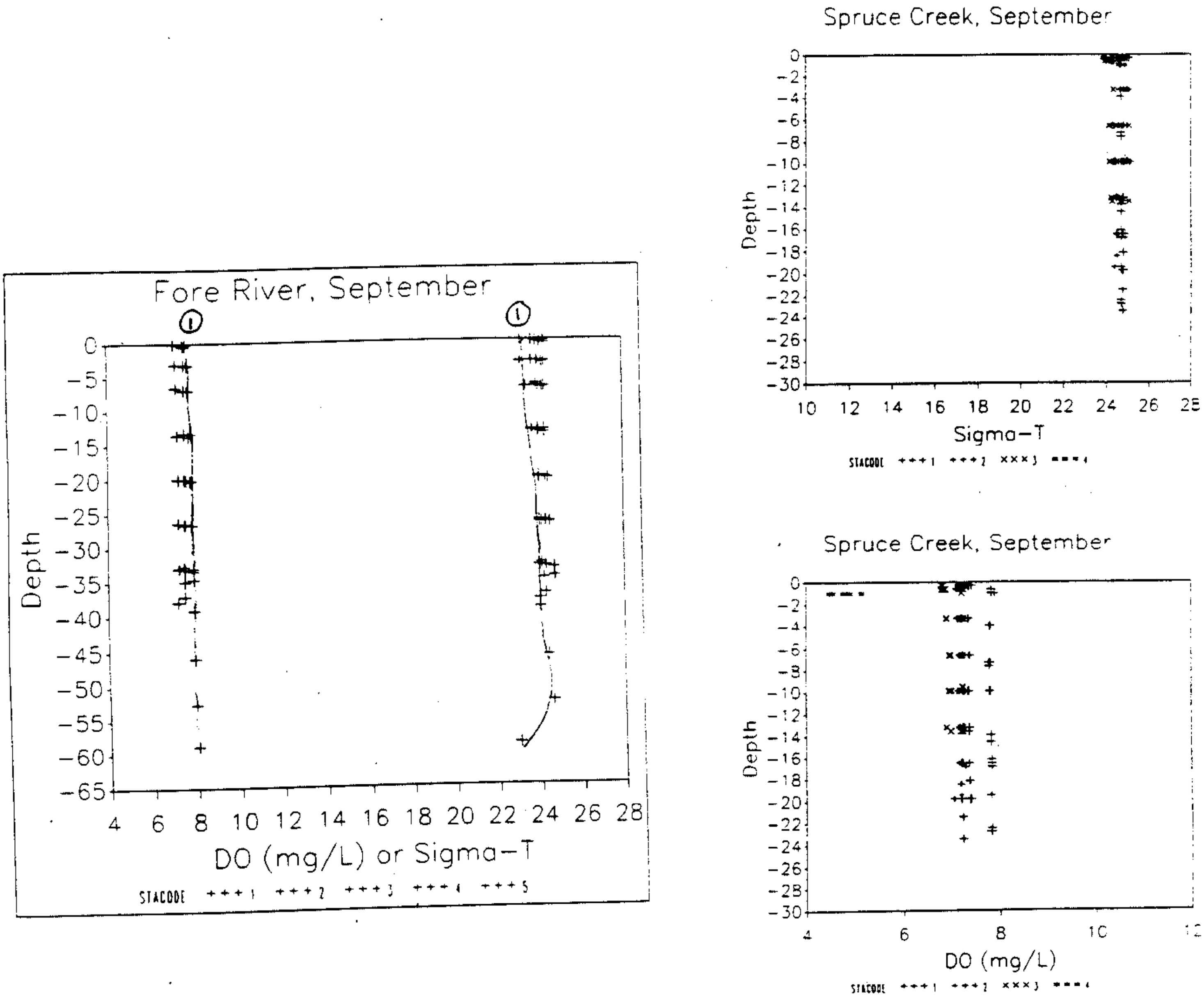


Figure A-9: Station profiles for DO (mg L^{-1}) and density (Sigma-T) for Fore River and Spruce Creek, two well-mixed systems with very weak vertical stratification. Station 1 is near the mouth of the system and the transect proceeded up the estuary.

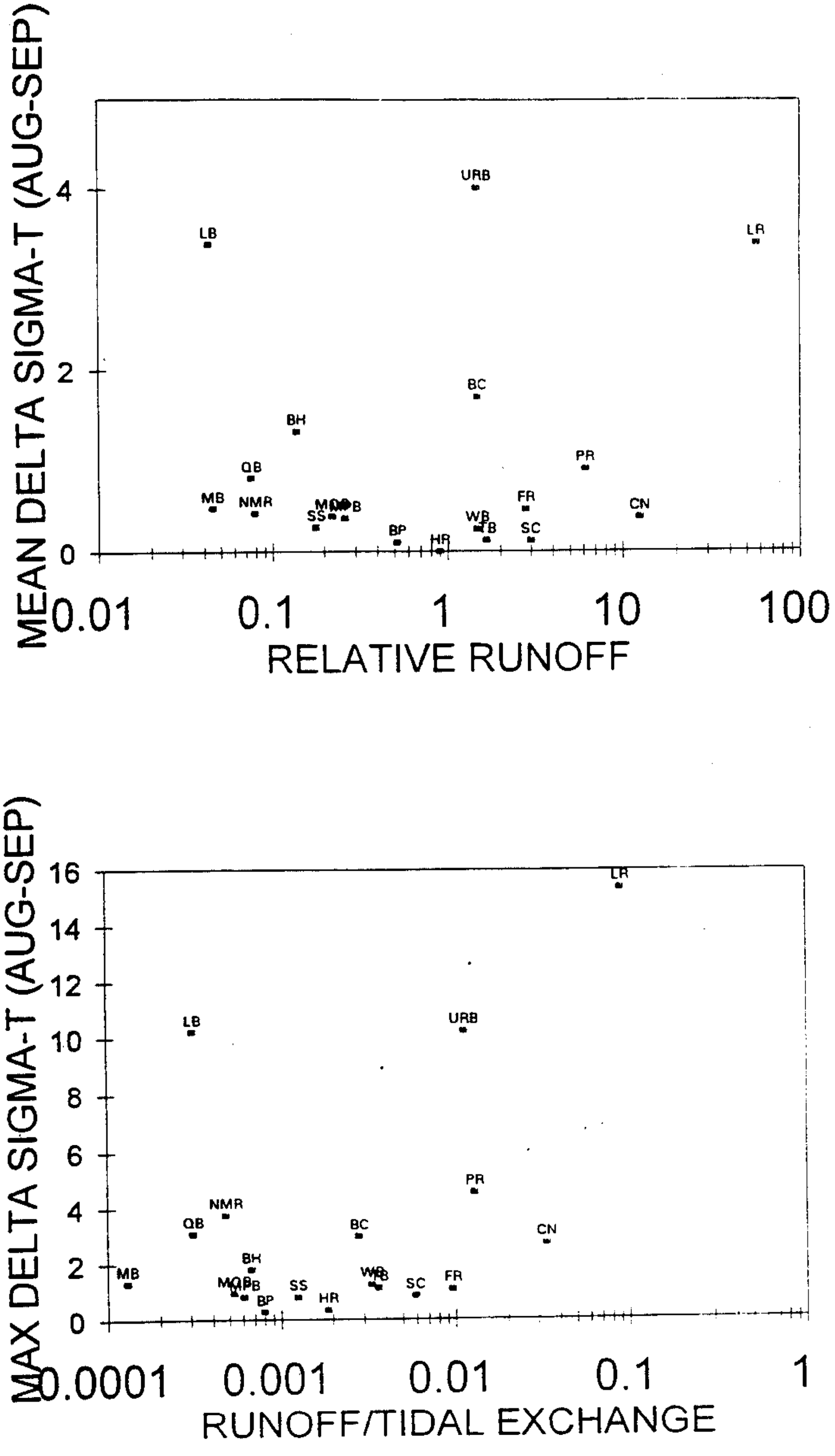


Figure A-11: Stratification indices vs. runoff indices for all systems.

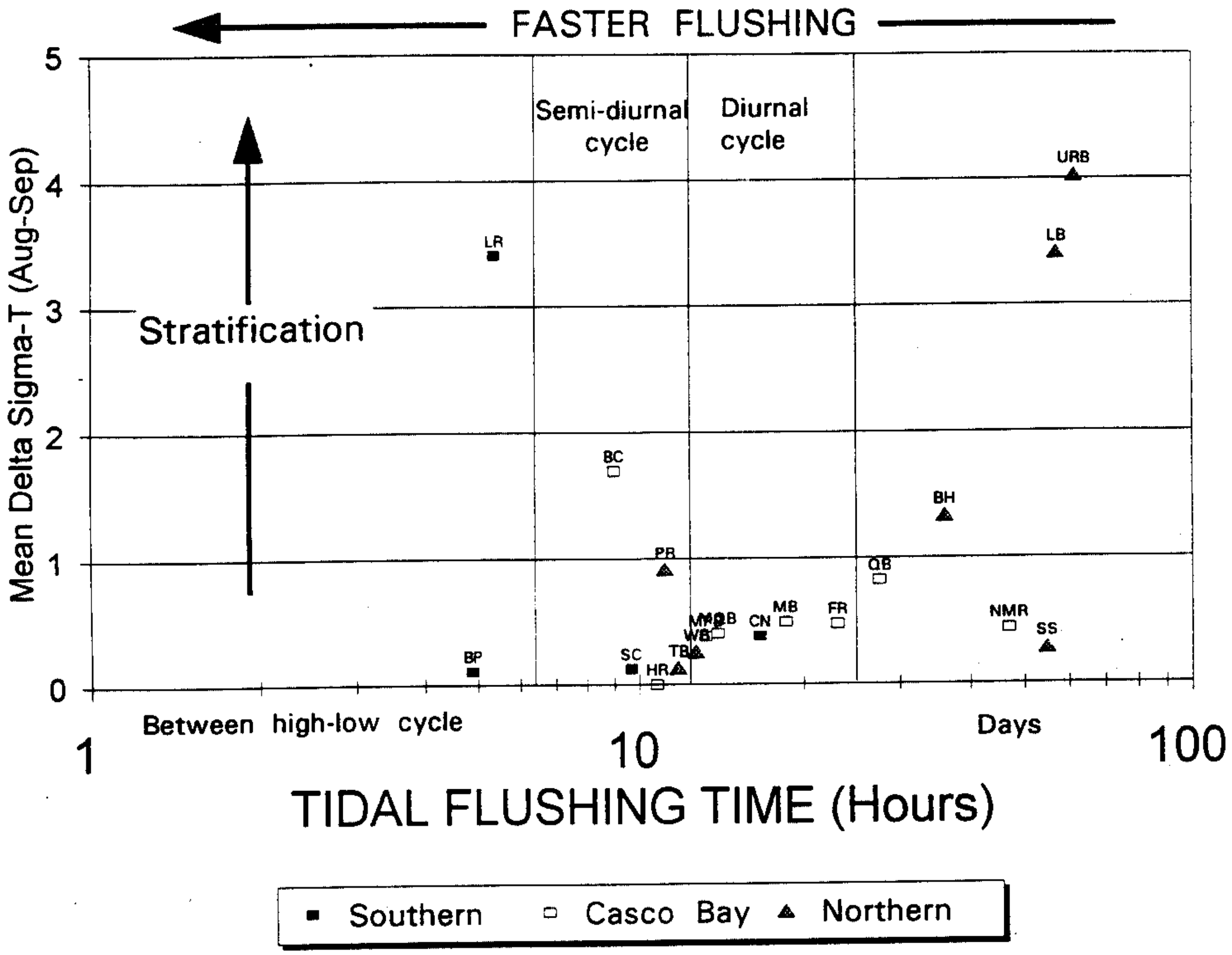


Figure A-12: Comparison of system attributes: Stratification vs. tidal flushing